NOAA SECTORAL APPLICATIONS RESEARCH PROGRAM (SARP)

ATTACHMENT TO PROJECT FINAL REPORT

PROJECT TITLE: Urban Supply Reliability Under Climate Change: Policy, Economics and Water Management

INVESTIGATORS: **Lead PI, Arizona:** Dr. Bonnie G Colby, Professor, University of Arizona, Department of Agricultural and Resource Economics, 1110 E North Campus Drive, Tucson Arizona 85721-0023, 520-621-4775, bcolby@email.arizona.edu

NOAA Grant Number **NA07OAR4310375**

TIME PERIOD ADDRESSED BY REPORT: 8/01/07 - 01/31/2011

Bonnie Colby and Elizabeth Basta

Submitted May 1, 2011

TECHNICAL RESEARCH REPORT

Note: Major portions of this report are adapted from Elizabeth Basta's graduate student thesis ("Urban Water Supply Reliability and Climate Change", M.S. Thesis, Department of Agricultural and Resource Economics, The University of Arizona, 2010). This thesis research was supported by the grant for which this document serves as the final report.

Acknowledgements: Colby and Basta acknowledge former and current faculty researchers and graduate research assistants on the University of Arizona project for their assistance and contributions over the years of the project. We specifically appreciate the editorial expertise provided by Lana Jones for this report. Complementary work which informed this project was supported by the National Oceanic and Atmospheric Administration's Climate Program Office through the Climate Assessment for the Southwest program at the University of Arizona, by the US Bureau of Reclamation, by the Freshwater Initiative of the Walton Family Foundation and by the US Department of Agriculture's Multistate Research Project, W2190, "Water Policy and Management Challenges in the West, USDA. The report represents the views of the author, not those of University of Arizona or of the agencies providing support for this work. Any errors are the responsibility of the authors.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Water use in the western United States occurs in many sectors including agricultural, industrial, municipal, and environmental. Rights to use water typically can be sold or leased subject to federal and state policies. In the past century many major water infrastructure projects, such as dams, reservoirs, and water transport canals, were completed in the western U.S. to increase water supplies and water reliability. However, claims to water are fully allocated in many regions, leading to competition for water use between and within sectors. For example, agricultural water users may be competing with each other and with municipalities to secure additional water supplies. Competition for water supplies has led to the development of water markets, with market transactions providing a mechanism for efficient reallocation of water. Water transfers are voluntary agreements between two entities, and enable water to move from lower value uses to higher value uses since those who place a higher value on the water are willing to pay more to acquire it. Often, lower value uses are agricultural and higher value uses are municipal (Brewer et al. 2007). Driven largely by population growth, municipal water uses are increasing and municipalities are willing to invest in order to secure water sources to meet projected water use.

The substantive research report is divided into two broad sections. The first section develops indicators of urban water supply reliability and then illustrates their application to three specific western cities. The second section develops econometric models of urban water transactions.

URBAN WATER SUPPLY RELIABILITY—DEVELOPMENT OF INDICATORS AND APPLICATION TO CASE STUDIES

In discussing each city, we look at water supply reliability, supply vulnerability and resiliency, adopting the following definitions, “System performance can be described from three different viewpoints: (1) how often the system fails (reliability), (2) how quickly the system returns to a satisfactory state once a failure has occurred (resiliency), and (3) how significant the likely consequences of failure may be (vulnerability)” (Hashimoto et al. 1982, p15). Several different aspects of a city’s water supply contribute to its reliability, vulnerability, and resiliency such as: diversity and governance of supply sources, water storage and back-up supplies, rate of water use growth, ability to secure new water sources, and vulnerability to climate impacts (Lang 2003). Each of these aspects is discussed in detail for each city.

This case study portion of the research explores quantitative measures which can be useful to municipalities for their own internal use, and which could also be useful means to compare across municipalities. For this reason we discuss several reliability and vulnerability indicators from the literature, looking for indicators with relatively straightforward definitions and calculations, and which can be computed with available data.

INDICATORS FROM THE LITERATURE

The indicators used in this research are adapted from two articles (Lane et al. 1999 and Hurd et al. 1999), both of which examine water supply systems on larger geographic scales, one at the regional level, and one at the watershed level. Here we apply these indicators to a smaller geographic scale, municipal water supply systems. Some adaptations of the indicators are necessary to make them relevant on this smaller scale and to suit the different geographic regions. In an effort to compare indicator values across cities, all indicators are computed such that the higher the value of the indicator, the more stress in the system. The indicators as they appear in the literature are as follows:

Storage Vulnerability "Measure of region's ability to cope with extreme water events; by reservoir yield, which is approximated by consumptive demand divided by regional reservoir storage capacity (internal and upstream)," (Lane et al. 1999, p195)

Withdrawal ratio "Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems," (Lane et al. 1999, p196)

Natural Variability "Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of unregulated annual streamflow to the unregulated mean annual streamflow. Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes," (Hurd et al. 1999, p1401)

Groundwater Depletion "Ratio of average groundwater withdrawals in year [i] to annual average baseflow, reflecting the extent that groundwater use rates may be exceeding recharge. Regions with high depletion rates are vulnerable to long-run changes in hydrology," (Hurd et al. 1999, p1401).

Since the indicators discussed above in the literature do not include any indicators to evaluate resiliency, we developed an indicator based on the resiliency definition, "how quickly the system returns to a satisfactory state once a failure has occurred," (Hashimoto et al. 1982 p15). In the context of a surface water reservoir system, the speed of recovery from drought depends on the size of the system, average inflows, and the intensity of water use from the system. Our proposed indicator is as follows:

Reservoir System Resiliency A measure of a reservoir system's ability to recover from drought: 1) Reservoir capacity divided by average annual inflows; 2) Annual water use or system outflows divided by average annual inflows; 3) multiply both values together.

The limitation of this indicator is that it only applies to surface water reservoir systems and does not measure resilience of other water sources, such as groundwater.

The indicators presented in the literature and discussed above can aid in developing a quantitative picture of municipal reliability, vulnerability, and resiliency to drought and climate change. In the following sections, we address issues of calculating and using indicators, and whether the particular indicators selected are useful for the purpose of assessing actual municipal water supply systems. One advantage of developing quantitative indicators is to provide another method of evaluation beyond just a discussion of the issues.

CASE STUDY: TUCSON, ARIZONAOVERVIEW

Water supply sources in Tucson are groundwater, reclaimed water, and Colorado River surface water brought to the city through the Central Arizona Project (CAP) canal. The two main planning documents used for information on Tucson's water are: City of Tucson's "Water Plan: 2000-2050," updated in 2008 to reflect the progress and decisions made since the first installment; and Arizona Department of Water Resources (ADWR) Draft Demand and Supply Assessment for the Tucson Active Management Area (AMA) (ADWR, 2010b). Due to the information content and larger geographic area used for ADWRs Demand and Supply Assessment, it is used as a primary source and Tucson Water's "Water Plan" as a supplemental source.

The goal of ADWR is to halt groundwater overdraft and attain a "safe yield" use of groundwater for each AMA in Arizona by the year 2025. A safe yield or sustainable use of groundwater would mean that the use of groundwater would not exceed the amounts of natural or artificial groundwater recharge. To assess the ability of the Tucson area in attaining this goal, ADWR completed the Supply and Demand Assessment, which takes a detailed look at past water use by source and by sector and projects several future water use scenarios out to the year 2025.

ADWRs Baseline Scenarios 1-3 look at three levels of future water use, and then the scenarios are calculated again to reflect the effect of a shortage on the Colorado River. One additional scenario is calculated to reflect maximizing the use of reclaimed water. In total, seven scenarios are calculated with the only scenario coming close to achieving ADWRs goal of "safe yield" being the maximized reclaimed water use scenario. In calculating each scenario, the shifts in water supply sources and water use by sector, help provide an overall picture of water supply reliability and vulnerability.

Tucson's arid climate and growing population are pressing factors in evaluating the reliability, resiliency, and vulnerability of its water supply system. Understanding potential future water demands and potential future water supply shortages allows for planning to obtain a comfortable balance of water supply reliability, resiliency, and vulnerability.

The City of Tucson is the largest urban water provider in the metro area and supplies its obligated service area, which does not encompass the whole metro Tucson region. This study is concerned with the greater Tucson metro area and so water use information and data come from the Arizona Department of Water Resources (ADWR) for the Tucson Active Management Area (AMA). Water use information from the City of Tucson also is used to supplement and enhance information from ADWR. Figure 1 illustrates the Tucson Water's current service area, their obligated service area, and potential service area (City of Tucson and Pima County 2009).

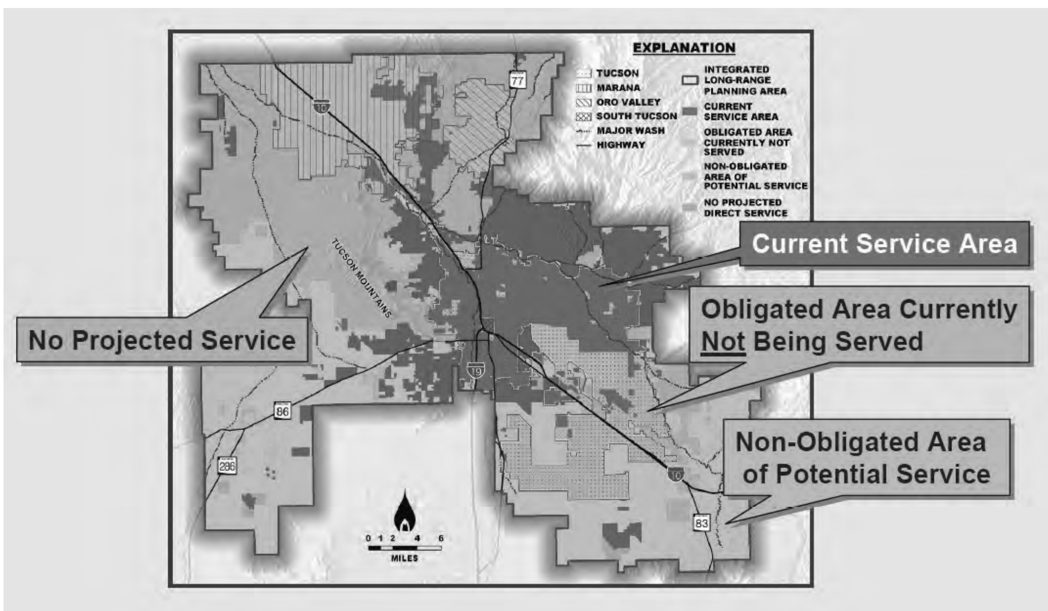

Figure 1 Tucson Water Service Area

The Groundwater Management Act of 1980 established the Tucson AMA, along with several other AMAs. The AMAs are urban areas with stricter groundwater use regulations, enacted due to years of overdraft. The AMAs are managed by ADWR. The Tucson AMA covers 3,866 square miles, with water use coming primarily from municipal, industrial, agricultural, and Indian users. Municipal uses are the highest share of overall water use (ADWR 2010b); Table 1 lists the major municipal water providers in the Tucson AMA.

Table 1 Major Municipal Water Providers in the Tucson AMA

Major Municipal Water Providers within the Tucson AMA	Community Water Company of Green Valley
	Flowing Wells Irrigation District
	Marana Water Department
	Metro Water District
	Oro Valley Water Utility
	Tucson Water

Industrial water use is primarily for metal mines, and “Indian water” is defined as water rights designated to Native American tribes through water rights settlements. Portions of the Tohono O’odham Nation Reservation are located within the Tucson AMA. Figure 2 is a map showing the layout of the City of Tucson, the Tucson AMA, and Pima County (Barker 2009).

Figure 2 Map of the City of Tucson, the Tucson AMA, and Pima County

The most recent publication from ADWR is the 2010 “Tucson AMA Draft Demand and Supply Assessment” (ADWR, 2010b). The assessment reports observed water use data from 1985-2006 and then projects three Baseline Scenarios for future water use for the period of 2007-2025. "Baseline Scenario One represents the lowest reasonable water demand, Baseline Scenario Three the highest reasonable water demand, while Scenario Two is a mid-level projection," (ADWR 2010b, p50). Figure 3 and Figure 4 show water use by sector (Municipal, Agriculture, Industrial, and Indian) for 1990 and 2010, with 2010 based on Baseline Scenario Two projections (ADWR 2010b).

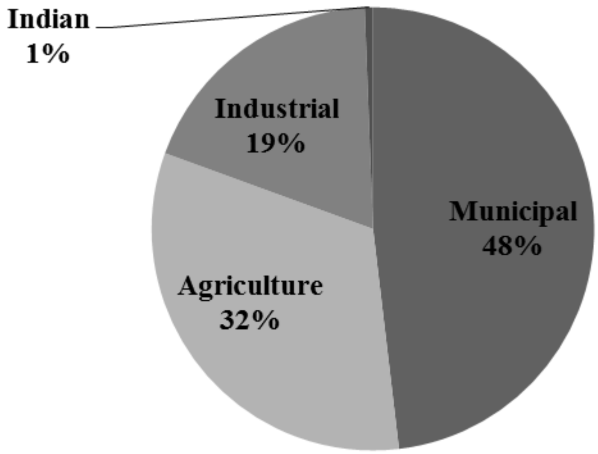

Figure 3 Tucson AMA Water Use by Sector, 1990

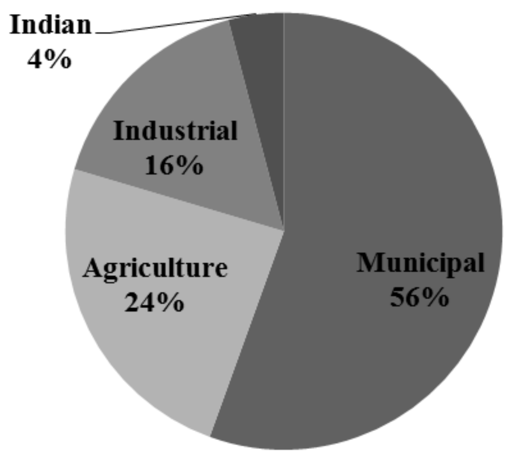

Figure 4 Tucson AMA Water Use by Sector, 2010 (projected)

In addition to the three Baseline Scenarios, ADWR includes three additional scenarios based on supply shortages and one scenario looking at reclaimed water maximization. The purpose of the assessment is to gain a better understanding of future water use scenarios and to see how the Tucson AMA may attain its Safe Yield goal of sustainable groundwater use by 2025. Several acronyms are used in this discussion; Table 2 provides a reference.

Table 2 List of Tucson Case Study Acronyms

ACRONYM	DESCRIPTION

ADWR	Arizona Department of Water Resources
AF	Acre Feet
AMA	Active Management Area
AWBA	Arizona Water Banking Authority
BOR	Bureau of Reclamation
CAGRD	Central Arizona Groundwater Replenishment District
CAP	Central Arizona Project
GMA	Groundwater Management Act
GSF	Groundwater Savings Facilities
ICS	Intentionally Created Surplus
USF	Underground Storage Facilities

Diversity and Governance of Supply Sources

Water supply diversity affects supply reliability since an urban area relying on several water sources has a more reliable system than if the area relied exclusively on one source. The system is less likely to fail so long as shortages in the sources are not highly correlated, that is they are not all subject to simultaneous shortage. Tucson, with its three sources of water, groundwater, effluent and Colorado River surface water, is diversified in its water supply portfolio. Shortages in these three supplies are unlikely to be highly correlated. However, each source has its own associated risks and benefits.

How each source is governed or managed also affects supply reliability. Issues ranging from water rights and priorities among uses to use restrictions on water sources all play a role in current and future water supply reliability.

Until the 1990's, groundwater was Tucson's only source of potable water. Although reliable historically, groundwater in this arid region is very slow to recharge and is therefore not resilient. Over time, the amount of groundwater pumped continually grew with the population until the amount pumped far exceeded the amount of natural recharge. Tucson still relies on groundwater, and the area still has vast groundwater reserves. However, state water regulations recognize that using more water than is recharged will eventually deplete the recoverable water, leaving water users continually more vulnerable to shortage. If surface water from the Colorado River were to be in shortage or if effluent supplies were interrupted, groundwater could be relied upon to serve the area. However, continuing cumulative overdraft is not a reliable strategy in the long run.

Groundwater for each AMA in Arizona is governed by the Groundwater Management Act of 1980 (GMA) with implementation of the Act overseen by ADWR. The goal for the Tucson AMA is to attain Safe Yield, or sustainable groundwater use, by 2025.

The majority of groundwater users are required to comply with one of the following in an effort to meet the Safe Yield groundwater sustainability goal by 2025: the Agricultural Conservation Program, the Municipal Conservation Program, or the Industrial Conservation Program (ADWR 2010b).

Reclaimed water is effluent that has been treated for re-use. Currently in Tucson effluent is treated to a quality suitable for, "turf and ornament landscaping, firefighting, toilet flushing, orchards, and the irrigation of some edible food crops," (City of Tucson 2008, p4-3). Reclaimed water has the unusual characteristic of increasing in magnitude with the population. However, using reclaimed water has implications for water quality and public satisfaction. Increasing reclaimed water use can improve system reliability as it frees potable sources to be used strictly for potable uses. The importance of maximizing reclaimed water use in the Tucson AMA is evident in the ADWR scenario projections. Findings suggest that only the scenario that maximizes the use of reclaimed water allows the Tucson AMA to be close to the Safe Yield goal by 2025 (ADWR 2010b).

Expanding the use of reclaimed water in the Tucson area is both an infrastructure capacity issue and an economic issue. Demand for reclaimed water is seasonal, since many customers are turf irrigators, such as golf courses. During peak water use seasons, the reclaimed water delivery system is often at capacity, where as the off-peak water use may be zero (City of Tucson 2007). Plans are in place to increase the amount of reclaimed water available for supply and to expand the ability to supply to new customers. Reclaimed water prices per Ccf are comparable to the lower range of potable prices (City of Tucson 2010).

The governance of effluent entitlements is based on several agreements with the following entities: the City of Tucson, Pima County, the Secretary of the Interior (Bureau of Reclamation), Metro Water, and the Town of Oro Valley. Total approximate effluent production in 2004 was 68,200 acre feet. Of this amount, the Secretary of the Interior is entitled to 28,200 acre feet, under provisions of the Southern Arizona Water Rights Settlement Act. As part of the settlement Tohono O'odham Nation will receive this water as treated effluent discharged to the Santa Cruz River to restore river flows (ADWR 2010a). Tucson area municipalities do not have rights to all of the effluent production, which could also affect future expansion of reclaimed municipal supplies.

Colorado River surface water is Tucson's most abundant source of renewable water. With the completion of the CAP canal and the addition of surface water to Tucson's water portfolio, overall water reliability improved since the area was no longer totally dependent on groundwater for meeting all potable water use. Although Colorado River surface water is a renewable water source, two significant factors may decrease its reliability overtime and increase Tucson's vulnerability to drought-induced water shortages. These factors are over-allocation of the Colorado River and climate change.

With respect to Colorado River water rights Arizona's CAP allocation is a low priority, or junior, use. The lower basin of the Colorado River has a total annual allocation of 7.5 million acre feet per year, with California being the most senior right holder of the lower basin states (AZ, CA, and NV). Arizona's annual CAP allocation is 2.8 million acre feet (Secretary of the Interior 2007).

Due to significant drought in the late 1990s and early 2000s and concerns about future shortages, the Bureau of Reclamation and the three Lower Basin States entered into a new Colorado River shortage agreement, where supply cutbacks are enacted depending on the elevation of Lake Mead. Since California has the highest priority allocation Arizona and Nevada are the two states subject to supply cutbacks.

Although Arizona holds a lower priority water right for Colorado River, and this affects CAP supplies during shortage declarations, there also exists a priority system within the CAP. How CAP water users are affected depends on their CAP priority. The highest priority users of CAP water are municipalities, which includes the Tucson metro area, other cities, and eleven Native American Tribes.

If municipalities served by the CAP do experience supply cutbacks at a future date, the supply reductions, "would be reduced on a proportional basis, and within each class on a pro-rata basis, based on the amount of water actually delivered to each entity in the latest non-shortage year," (City of Tucson 2008, pD-8). Therefore, if Tucson area municipalities are not using their full allocation, their cutbacks are based on their previous use, not their full allocation. For this reason and also to mitigate groundwater mining, one of Tucson Water's priorities is to maximize use of its CAP allocation. As of their 2008 Water Plan Update, the City of Tucson was able to accept and deliver about 50% of their CAP allocation. However with planned facility upgrades on the horizon, Tucson Water estimates that the majority of its service area will be served by renewable CAP supplies by 2012 (City of Tucson 2008). Figure 5 and Figure 6 show Tucson AMA Municipal Water Sources for 1990 and 2010, with 2010 based on Baseline Scenario Two projections (ADWR 2010b).

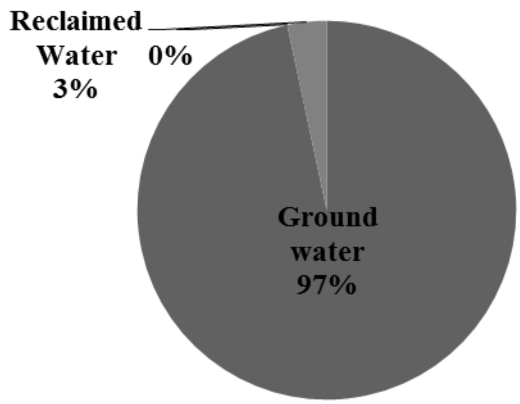

Figure 5 Tucson AMA Municipal Water Sources, 1990

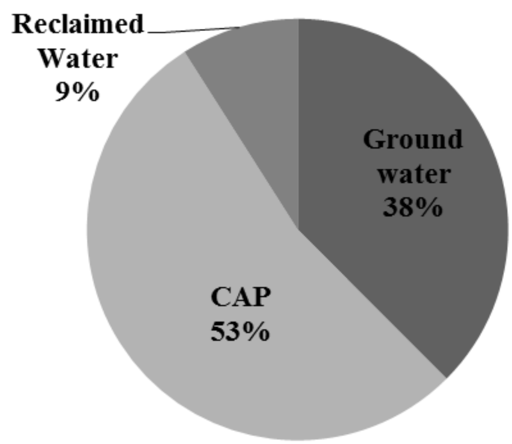

Figure 6 Tucson AMA Municipal Water Sources, 2010 (projected)

Water Storage and Back-up Supplies

The reliability of Tucson's CAP surface water is the product of the expansive reservoir storage system on the Colorado River and other water allocation arrangements in the Colorado River Basin and within the CAP (discussed previously). These arrangements include direct, local water storage for the Tucson AMA including water banking and back-up groundwater supplies and are not discussed in depth in this report. For more details see Basta (2010).

Rate of Water Use Growth

For the Tucson AMA, the rate of total water use growth is the sum of growth in the four primary water use sectors: municipal, industrial, agricultural, and Indian. Future municipal water use is highly dependent on population growth, and industrial water use in Tucson is largely dependent on mining operations. Agricultural water use is harder to project, as many unpredictable factors influence agricultural activity in the area such as crop prices, federal farm programs and conversion of agricultural land to urban use. Water use by Indian communities is dependent on Indian agricultural growth, which is expected to continue to increase (ADWR 2010b).

In order to analyze and plan for future water use growth, the ADWR uses their yearly projections of growth out to the year 2025 based on three water use scenarios. As actual water use data becomes available each year, ADWR can see how closely actual water uses are tracking with each of the projected scenarios. Future water use planning can then be re-evaluated depending on how current water use is matching up with previously projected water uses.

Since Tucson is a rapidly growing urban area, municipal water use makes up the largest sector of water use. Population is the primary driver of municipal water use, so focusing on population growth in Tucson is imperative for water supply reliability planning. Table 3 illustrates projected water use by sector for the year 2025 for all three Baseline Scenarios (ADWR 2010b).

Table 3 Projected Tucson AMA Water Use by Sector and Scenario

	Scenario One	**Scenario Two**	**Scenario Three**
Municipal Use	**251,018**	**279,264**	**308,237**
Agriculture Use	**57,038**	**71,342**	**112,245**
Industrial Use	**55,682**	**63,782**	**71,282**
Indian Use	**19,033**	**21,455**	**34,043**
TOTAL	**382,771**	**435,843**	**525,807**

As a comparison, Tucson Water forecasts four water use scenarios (A, B, C and D) out to the years 2030 and 2050 based on projected changes in their area of service and implementing further demand management strategies. The demand management strategies would aim to cut potable water use by 7.5% while also decreasing internal system water losses. Together these two strategies forecast a total cut of at least 10% in potable use (City of Tucson, 2008). Scenario A would provide water to the current obligated service area, accompanied with stricter demand management strategies; Scenario B would provide water to the current obligated service area, but without any further demand management strategies; Scenario C would provide water to the potential service area accompanied with stricter demand management strategies; Scenario D would provide water to the potential service area, but without any further demand management strategies. Table 4 displays water use for Tucson Water under each of the four scenarios and for the years 2000, 2030, and 2050 in acre feet (City of Tucson, 2008).

Table 4 Tucson Water Use Scenarios for the Years 2000, 2030, and 2050

Scenario	Year 2000	Year 2030	Year 2050
A	128,141 af	180,000 af	215,000 af
B	128,141 af	200,000 af	235,000 af
C	128,141 af	200,000 af	235,000 af
D	128,141 af	220,000 af	255,000 af

Ability to Secure New Water Sources

Tucson's ability to obtain new sources of water is based on a combination of economic, environmental, and political decisions. Current short term supply augmentation ideas are all based on increasing Tucson's use of Colorado River surface water. To increase supplies in the short term Tucson's possibilities range from reallocations of CAP water or leases/purchases of water from other entities. For example, Tucson could push for a higher portion of CAP allocation or lease excess water from farmers or Indian Tribes during dry years.

In looking toward long term possibilities of acquiring new sources, the most recent developments involve the creation of the ADD Water Project. The ADD Water Project, which stands for Acquisition Development and Delivery of new Water supplies, is headed by the Central Arizona Project and forms partnerships between the three Arizona Counties receiving deliveries of CAP water (Central Arizona Project 2010a). Instead of each individual municipality looking for and developing its own new water supplies, the ADD Water project will seek out new supplies and work out a framework for how to allocate the new supplies and how to share the costs. Delivery of water under this project would be through the CAP canal. Although a final framework is still in the works, if the project is successful, Tucson as well as other Arizona municipalities can enhance their water supply reliability while collectively sharing the costs.

Where the new supplies will come from is still unknown, but prospects include currently undeveloped groundwater and surface water supplies in Arizona, increased use and treatment of effluent, as well as desalination. Arizona is investigating construction of a seawater desalination plant in either a U.S. or Mexican coastal community (City of Tucson 2008). The idea would be to construct a facility to provide water to that coastal community and in exchange, that community's higher seniority Colorado River water rights would be transferred to Tucson and any other participating partners (City of Tucson 2008). A project of this size would not be realized for years or decades to come, and many economic, environmental, and political concerns all play a crucial part in its plausibility.

Lastly, Arizona is participating in Intentionally Created Surplus projects. Intentionally Created Surplus (ICS) is a mechanism for creating an intentional surplus of water in Lake Mead, accruing "credits" for the surplus, and then being able to use the "credits" to withdraw the water at a later point in time (SNWA 2009b). ICS projects can be used to enhance CAP supply reliability. The manner in which ICS projects will directly benefit the Tucson region is not clear at this time, but they are a potential tool that could augment supplies for Tucson and other parts of Arizona. The amount of water received by the states participating in ICS projects depends on the amount of water conserved and how the project financing is shared

Two ICS projects involving Arizona are the Yuma Desalting Plant pilot project and Drop 2 Reservoir (Bureau of Reclamation, 2010d). The Yuma Desalting Plant (YDP) was constructed in 1992 to treat brackish agricultural drainage. Treating the water allows it to count towards Mexico's Colorado River allocation and frees up additional sources for the lower basin states. Currently, the brackish water is too saline to qualify as part of Mexico's allocation, but operations at the plant ceased shortly after construction due to flood damage on the delivery canal. Pilot operations are underway to test its current desalting efficiency and determine whether costs can be lowered and efficiency improved with new technology. The plant will run at one-third capacity for 12-18 months (Colorado River Project 2010b). Although Arizona will receive a small amount of water from the pilot project, the potential for future YDP operations is dependent on the success of the pilot run.

The Drop 2 Reservoir will store water that is ordered by Lower Basin irrigation districts on the Arizona/California border and released from Lake Mead, but then ends up not being used and flowing to Mexico. Changes in the weather and increases in precipitation are common reasons for water to be ordered and released from Lake Mead, but then not used by irrigators since the water takes around three days to travel from Lake Mead to the irrigation districts (Holmes 2010). The Drop 2 Reservoir will allow the irrigation districts to utilize any stored reservoir water, which keeps more water in Lake Mead. By contributing to the project financing, Arizona will receive a total of 100,000 acre feet of water from the project, but a maximum of 65,000 acre feet per year, beginning in 2016 (Bureau of Reclamation, 2010d). Again, the direct benefit to the Tucson area is not known, but similar future projects could contribute to new supplies for Tucson. Deliveries from the reservoir are scheduled to begin in October of 2010 (Colorado River Project 2010a).

Vulnerability to Climate Impacts

Although climate change predictions point towards increasing precipitation variability with more extreme droughts and floods, the magnitude of these predictions is much more challenging to forecast. Climate change models have not yielded consistent results regarding precipitation changes in the Colorado River Basin. However, these models have shown consistency in forecasting temperatures. "Models show increased Colorado River Basin temperatures in both summer and winter, with seasonal increases of 2 degrees Celsius by 2050 and annual increases of 4-5 degrees Celsius by 2099," (Garfin et al. 2007, p70). Higher temperatures could affect both the supply and the amount of water used leading to a changing balance of Tucson's water reliability, resiliency, and vulnerability.

With respect to supply, higher temperatures could lead to less precipitation infiltrating into Rocky Mountain soils during summer and fall storms, which could have an effect on how much spring snowmelt reaches the Colorado River and the basin's reservoirs. Higher temperatures could also affect supply by causing snowmelt to occur earlier in the spring, and increasing evaporation rates throughout the year. Natural groundwater recharge in the Tucson area could also be reduced if precipitation decreases, exacerbating aquifer overdraft. With respect to water use, higher temperatures could cause farmers to consume more irrigation water, and urban users to consume more water for cooling and landscaping needs (Garfin et al. 2007).

Even without the uncertainties of human-induced climate change impacts, the Colorado River is vulnerable to a large range of natural variability. Tree ring reconstructions of drought over the past 500 years show that longer and more severe droughts than we have experienced in recent history are possible on the River. Since severe droughts could lead to shortages on the River, ADWR uses their three baseline scenario projections for water supply and water use to project three additional scenarios based on CAP shortages.

For each of the CAP shortage scenarios, water use remains the same as the Baseline Scenarios, but CAP shortages decrease supply. Using computer simulations of supply shortages for the years 2012-2019, ADWR looks at the total supply impacts for each year. The yearly shortages for the period range from 320,000-480,000 acre feet depending on the Lake Mead elevation. The total shortage amount for the eight years is 3,280,000 acre feet. For each scenario, ADWR states that the shortages will mostly affect those using excess CAP water instead of those who have CAP contracts, such as municipalities.

The previous sections discussed the diversity and governance of supply sources, water storage and emergency back-up supplies, rate of water use growth, ability to secure new sources, and vulnerability to climate impacts for the Tucson AMA and how each of these areas affect water supply reliability and vulnerability. This next section looks at what measures Tucson employs to evaluate its own water reliability and vulnerability status.

Water Supply Reliability and Vulnerability: Tucson Self-Assessment

The City of Tucson in its 2009 Annual Drought Monitoring Report discusses several indicators used to assess the area's current drought conditions in the context of water supply and use for the City. The report is in accordance with the City of Tucson's Drought Preparedness and Response Plan developed in 2006, which calls for an annual update on current drought impacts to the area's water supply sources. Arizona state legislation passed in 2005 requires all community water providers to prepare a Drought Preparedness Plan and submit the Plan to ADWR (ADWR 2010c).

Regional indicators the City assesses are the statuses of the Colorado and Santa Cruz Watersheds. For the Colorado, they look at snow water equivalent snowpack and reservoir changes in Lakes Mead and Powell. For the Santa Cruz they use short term and long term watershed drought conditions as established by ADWR. Tucson also looks at four local system indicators: Aquifer Storage Index, Potable Production Capacity Index, Reclaimed Production Capacity Index, and Gallons Per Capita Per Day water production levels.

Colorado River Status When looking at the status of the Colorado River, the first factor is annual snowpack. The second factor is to look at any reservoir level changes from the previous year for Lakes Mead and Powell. For example, in Spring 2009 there was 1.5 million acre feet more of storage in both reservoirs compared to Spring 2008. Due to these conditions, the Secretary of the Interior did not declare a shortage on the Colorado River (City of Tucson 2009).

Santa Cruz Watershed Drought Status For this indicator Tucson Water looks at the drought status of the Santa Cruz Watershed, which is established by ADWR (City of Tucson 2009). As of spring 2009 the status is stated as being, "abnormally dry," (City of Tucson 2009).

"Aquifer Storage Index (ASI): captures the net effects on water table levels from pumping and from natural and artificial recharge. It is a measure of the change in water storage volume relative to a base year of 2000. Tucson Water's production wells are grouped into 11 regions of hydrologic similarity for this calculation. Each region is represented by one average water level, simplifying water level change comparison," (City of Tucson 2009, p10). The year 2000 is the baseline with an index level of 0.0 and the year 2003 is the lowest index level to date at -9.3. The value for 2007 is 11.9, and while a more current value in not reported, the report states that the index has continued to steadily rise since 2003 (City of Tucson 2009).

"Potable Production Capacity Index (PPCI): a ratio of potable production capacity available for the coming year (in millions of gallons per day, mgd) divided by the predicted maximum 30-day demand period for the upcoming year (in mgd). An index score of 1.1 or higher is considered good; lower than 1 indicates some degree of system stress. Production Capacity = 184.2 MGD; Forecasted Max 30-Day Demand (2008) = 148.28; 184.2/148.28 = 1.24," (City of Tucson 2009, p11).

"Reclaimed Production Capacity Index (RPCI): a ratio of maximum reclaimed water production capacity for the upcoming year to the peak day forecast for reclaimed water demand for the upcoming year. An index score of 1.1 or higher is considered good. Production = 33.5 MGD; Demand = 31.8 MGD; 33.5/31.8 = 1.05," (City of Tucson 2009, p12). Since the City is below the threshold value of 1.1, we can infer that reclaimed production capacity is under some degree of stress.

"Gallons Per Capita Per Day (GPCD): the total potable water produced for the previous year divided by the estimated service area population for that year. The 2008 report for GPCD is 140.4, down from 150.7 reported in 2007," (City of Tucson 2009, p11).

Tucson Water Supply Reliability, Vulnerability, and Resiliency Indicators

This final section looks at water supply reliability, vulnerability, and resiliency from a quantitative perspective using observed and projected data on water use in the Tucson AMA. Quantitative indicators developed in this section are Storage Vulnerability, Withdrawal Ratio, Natural Variability, and Groundwater Depletion. Discussion and interpretation of the indicator values follows after all indicator calculations are explained, and in the chapter conclusion.

The primary source of data used to calculate the indicators is ADWRs 2009 projections for Baseline Scenario Two, unless stated otherwise.

Storage Vulnerability *"Measure of region's ability to cope with extreme water events; by reservoir yield, which is approximated by consumptive demand divided by regional reservoir storage capacity (internal and upstream),"* (Lane et al. 1999, p195).

The size of the Colorado River reservoir storage system and the number of entities it serves proves difficult when trying to evaluate the Tucson AMAs precise benefit from the vast storage system. In modifying this indicator for the Tucson AMA we use storage of water that is legally available for use during times of drought or Colorado River shortage. Also, since the indicator definition is a measure of a region to cope with extreme weather events, calculating storage that can be used when there are shortage declarations on the Colorado River is more applicable to the design of the Tucson AMA water system. Although Tucson has access to groundwater reserves, we do not include them in this calculation. Groundwater overdraft has long been a problem in the Tucson AMA, so focusing on the efforts of the AMA to build storage reserves that do not deplete groundwater reserves when used, is more applicable for Tucson.

The data needed to calculate the indicator include a measure of consumptive water use and a measure of total water in storage that is accessible during periods of water shortage, and does not deplete groundwater reserves. Consumptive water use is approximated using 2009 annual water use projections for Tucson AMA Baseline Scenario Two. For water storage values, total Long Term Storage Credits as reported in ADWRs 2009 Long Term Storage Account Summary are used to calculate total water in storage.

Total projected 2009 AMA consumptive water use = 371,210 acre feet (ADWR 2010b). Total Tucson AMA Long Term Storage Credits sum to 800,380.04 acre feet (ADWR 2010d). Annual projected water use (371,210 af) divided by available storage (800,380.04 af) = 0.46.

The storage number used reflects AMA Long Term Storage Credits as a whole. Individual municipalities and entities within the AMA accrue their own storage credits and so may be subject to differing ratios of storage to water use. However, Long Term Storage Credits can be leased, sold, and gifted, so individual credits can be transferred to another party given that the new party qualifies for Long Term Storage Credits (ADWR 2010e).

Withdrawal ratio *"Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems,"* (Lane et al. 1999, p196).

To calculate this indicator we need, first, a value that represents annual water withdrawals in the Tucson AMA. Second we need a value that represents the sum of internally generated water and water imports. For both data needs we use projected data from ADWRs Baseline Scenario Two for the year 2009. In measuring the first part, annual withdrawals, we approximate the value using projected 2009 annual AMA water use, which is the sum of water use from each sector, municipal, industrial, agriculture, and Indian. Also included is riparian water use, since a measurable amount of water is used by riparian areas. Total projected annual AMA water use for 2009 is 373,985 acre feet (204,067 af (municipal); 61,082 af (industrial); 91,089 af (agriculture); 14,972 af (industrial); 2,775 af (riparian)) (ADWR 2010b).

To obtain a value for the second part of the equation, internally generated water plus water imports, we look at the sum of water sources available for use in the AMA from CAP surface water, reclaimed water, and groundwater.

Beginning with CAP surface water, we use the total amount of CAP allocation available for use in the Tucson AMA, which is 215,333 acre feet. Although the full allocation amount is not currently being consumed, the amount reflects what is available for use. The reason the full allocation is not being used is due to current capacity constraints at recharge and recovery sites. For example, Tucson Water, the largest municipal water provider in the AMA is recovering about 70% of its CAP allocation (CAP 2010b). Any CAP allocations that are accepted at recharge sites, but not recovered for consumption, are counted toward storage.

For groundwater, calculating annual groundwater recharge is complex since recharge can be natural, artificial, or incidental. Net natural recharge is any recharge that flows into Tucson's groundwater aquifers from precipitation, minus any outflow into other groundwater aquifers, which is not accessible to the Tucson AMA.

Artificial recharge refers to water that is recharged into the aquifer, but not available for withdrawal at a later date. The purpose of artificial recharge is to reduce groundwater overdraft, so artificial recharge values are not counted towards available groundwater withdrawals. Examples of artificial recharge are the mandatory 5% cuts to the aquifer for long term water storage, and the CAGRD.

The final category of groundwater is incidental recharge. We do count types of incidental recharge as available groundwater since this water is considered available for withdrawal. An example of incidental recharge is water used for landscaping or agriculture, in which a percentage of that percolates into the ground and reaches the groundwater table, thereby recharging groundwater. Another example is CAP canal seepage that also reaches the groundwater table. This source is carefully calculated by ADWR and included in projected water use and supply assessments.

In summing the two types of groundwater recharge that are available for withdrawal, net natural groundwater recharge and incidental types of recharge, the total projected groundwater supply for 2009 Baseline Scenario Two is 119,481 acre feet.

The last supply source is reclaimed water. One could argue that including reclaimed water is double counting of water, but since using reclaimed water is an important mechanism for augmenting supplies and meeting demands, we include reclaimed water in the supply calculation. ADWR also lists reclaimed water amounts as water supply, and the total projected 2009 Baseline Scenario Two amount is 19,262 acre feet.

Taking the first part of the equation, total 2009 AMA projected water use is 373,985 acre feet. Adding together available supply from surface water, 215,333 acre feet; groundwater, 119,481 acre feet; and reclaimed water 19,262 acre feet, the total available water is 354,076 acre feet. Calculating the Withdrawal Ratio, total projected water use (373,985 af) divided by total available water (354,076 af) = 1.06.

Natural Variability *"Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of unregulated annual streamflow to the unregulated mean annual streamflow. Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes,"* (Hurd et al. 1999, p1401).

Since Tucson's surface water supply is Colorado River water, using the coefficient of variation for unregulated Colorado River streamflow is the most logical modification of the indicator for the Tucson AMA. With the Colorado River we can look at the observed gauge record, as well as flow reconstructions from tree rings. Observed data between 1906-1995 show a coefficient of variation of 0.28, while observed and reconstructed data from 1490-1997 show coefficients of variation that range from 0.27-0.31 (Woodhouse et al. 2006).

Groundwater Depletion *"Ratio of average groundwater withdrawals in year [i] to annual average baseflow, reflecting the extent that groundwater use rates may be exceeding recharge. Regions with high depletion rates are vulnerable to long-run changes in hydrology,"* (Hurd et al. 1999, p1401).

For calculation of this indicator we need values for total groundwater withdrawals and for total annual average baseflow. We use ADWRs Baseline Scenario Two 2009 projections to obtain both values. Beginning with groundwater withdrawals, we approximate withdrawals using a sum of the total projected annual groundwater use from the various sectors (79,723 af, (municipal); 59,148 af (industrial); 87,454 af (agriculture); 1,043 af (Indian); and 2,775 (riparian)). ADWR indicates that groundwater use for agriculture includes direct groundwater use, as well as CAP water used in-lieu of groundwater at GSFs. When CAP water is used in-lieu of groundwater, the groundwater will be used at a later date, so for ADWR accounts, the groundwater is listed as used even though its actual withdrawal will be in the future. Using 2009 Baseline Scenario Two projections, the total annual groundwater use is 230,143 acre feet.

In calculating a value for average annual baseflow, this part of the equation is modified for Tucson to include all projected groundwater recharge, natural, artificial, and incidental for 2009. Natural recharge is net natural recharge from area snowpack and precipitation. For artificial recharge we include the CAGRD contributions and the 5% cuts to the aquifer from long term storage, since these are groundwater recharges that are not available for withdrawal in the future. For incidental recharge we include incidental recharge values listed for all sectors (municipal, industrial, etc.) as well as other types of recharge that is counted as usable supply, such as CAP canal seepage. Including all types of recharge allows for the calculation to reflect groundwater use versus groundwater offsets, whether the groundwater recharge is available for use, or not. Net natural groundwater recharge is listed as 77,356 af; artificial recharge is 29,149 af; and incidental recharge is 42,125 af, for a projected 2009 total of 148,630 acre feet (ADWR 2010b).

Calculating the indicator, annual groundwater use (230,143 af) divided by groundwater recharge (148,630 af) = 1.55. As is well documented, the Tucson AMA is using groundwater well in excess of recharge.

Reservoir System Resiliency *A measure of a reservoir system's ability to recover from drought: 1) Reservoir capacity divided by average annual inflows; 2) Annual water use or system outflows divided by average annual inflows; 3) multiply both values together.*

Applying this indicator for Tucson we use the Lower Colorado River reservoir system. The first value needed is total reservoir capacity. The primary storage reservoirs on the Lower Colorado River are Lakes Powell and Mead with a combined storage capacity of 54,752,000 acre feet (Bureau of Reclamation 2010a and 2010b). These two reservoirs are used since they are the largest and most important for Colorado River system management. To find a value for average annual inflows we use the mean value of streamflow using the existing observed record and also the record reconstructed using tree rings, which is estimated to be about 15 million acre feet (SNWA 2010). The final value needed for the indicator calculation is average annual outflows or water use from the system. The upper and lower Colorado River Basins both have an annual allocation of 7.5 million acre feet of water. The lower basin is using their full 7.5 million acre foot allocation, but the upper basin is not. Upper basin uses are about 4.2 million acre feet per year (Bureau of Reclamation 2008). Along with upper and lower basin uses, there is also an annual 1.5 million acre foot allocation for Mexico, which is delivered in full each year (Secretary of the Interior 2007).

To calculate current Colorado River water use we sum the upper basin use of 4.2 million acre feet, the lower basin use of 7.5 million acre feet, and Mexico's allocation of 1.5 million acre feet, which equals 13.2 million acre feet per year of Colorado River use.

The first equation for the indicator calculation, reservoir capacity (54,752,000 af) divided by average annual inflows (15,000,000 af) = 3.65. The second part of the equation, annual water use (13,200,000 af) divided by average annual inflows (15,000,000 af) = 0.88. Lastly, multiplying both parts together, 3.65*0.88 = 3.212.

Summary of Tucson Area Case Study

Examining the indicator values, some strengths and weaknesses emerge for the Tucson AMA with respect to their water supply system. The Storage Vulnerability indicator illustrates that projected 2009 AMA water uses are less than half of the amount the AMA has in storage, which shows the

AMA's strength in storing water for future use. The Withdrawal Ratio and Groundwater Depletion indicators are both greater than one, signaling that the AMA general water use and groundwater use are outpacing water supply. Natural variability on the Colorado River is not extreme, but given the high water use on the system, and current drought effects, even moderate variability is proving to be a challenge. Finally, the size of the Colorado River reservoir system coupled with annual allocations that are greater than average annual inflows indicates that the system is not as resilient as other reservoir systems with smaller inflow to capacity ratios and smaller annual water use to inflow ratios.

CASE STUDY: LAS VEGAS, NEVADA

OVERVIEW

Southern Nevada Water Authority (SNWA) is the umbrella water supply and management organization in the Las Vegas metropolitan area charged with overseeing and augmenting the area's water supplies. Currently Las Vegas is dependent on the Colorado River for 90% of its consumptive use and groundwater for 10%. Although Las Vegas' allocation of Colorado River water is 300,000 acre feet per year, the city is allowed to intake a significantly higher amount through its return flow credit program. The return flow credit program treats and returns water to the Colorado River via the Las Vegas Wash, so as long as total net consumption does not exceed 300,000 acre feet, the city is in compliance.

As the population of Las Vegas continues to grow SNWA has long been searching for viable water supplies to add to its overall water portfolio. The primary source of augmentation will be the development of additional groundwater sources outside of the Las Vegas area. Exact amounts are unknown at this time due to pending permits and approvals by the State Engineer, but resource scenarios include 134,000 acre feet per year from the Clark, Lincoln and White Pine Counties Groundwater Development Project. Along with groundwater, other sources include utilization of Intentionally Created Surplus and banked water sources, along with increased demand management efforts. The conservation goal for Las Vegas is to decrease gallons per capita day (GPCD) from 250 to 199 by the year 2035. The full planning horizon for Las Vegas extends through the year 2060.

This research offers additional methods for cities and utilities to examine their water supply sources and to identify deficiencies in reliability and vulnerability. Indicators relating to groundwater use, imported water, storage capacity, etc. will add to the way we look at and analyze water resources.

Similar to Tucson, the climate of the Las Vegas metro area is arid, and in recent years the area has experienced periods of extremely high growth rates. The current population of the Las Vegas area is around two million (SNWA 2009b) and 90 percent of the water supply is from the Colorado River

(SNWA 2009b). The remaining ten percent of the water supply is from groundwater and reclaimed water. Water use in the Las Vegas area is composed of residential uses (59%), commercial and industrial uses (14.5%) resorts and golf courses (14%), schools, parks, and common areas (10%), and other (2.5%). Figure 7 illustrates displays water use by sector (SNWA 2009b).

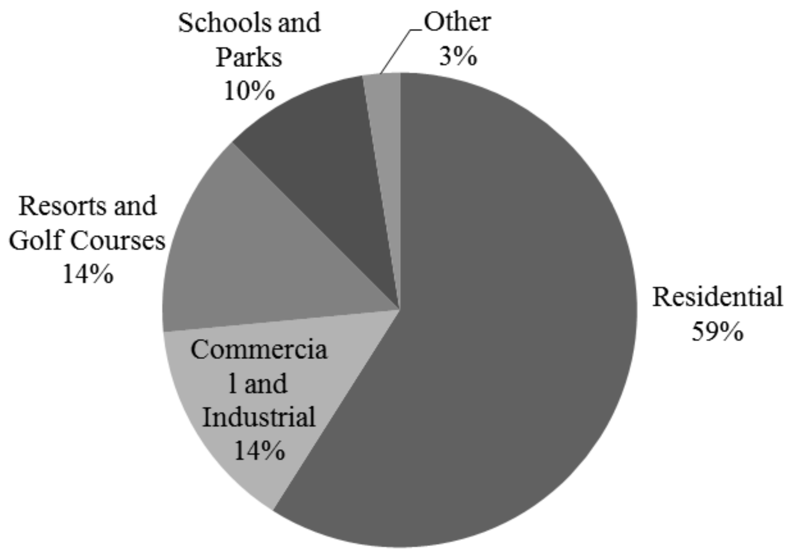

Figure 7 Las Vegas Area Water Use by Sector

Several separate municipalities are part of the Las Vegas area and in 1991 a partnership between seven water and wastewater agencies in the area formed the Southern Nevada Water Agency (SNWA). Table 5 lists the seven SNWA member agencies.

Table 5 SNWAs Seven Member Agencies

The Seven Municipal Member Agencies that Comprise SNWA	Big Bend Water District
	Boulder City
	Clark County Water Reclamation District
	Henderson
	Las Vegas
	Las Vegas Valley Water District
	North Las Vegas

SNWA is now the wholesale water provider and is, “responsible for water treatment and delivery, as well as acquiring and managing long-term water resources for Southern Nevada,” (SNWA 2009b). In order to reflect water supply reliability, vulnerability, and resiliency in the Las Vegas area, data and information from SNWA is used whenever possible. The primary information source from SNWA is their "Water Resource Plan," which is reviewed on an annual basis and updated when needed. The most recent revision is from 2009 and incorporates water resource planning based on population growth out to the year 2060, while also looking at the impacts on Colorado River declared shortages on municipal water supplies. Figure 8 depicts the greater Las Vegas area (Forensic Science Center 2010) followed by a table of acronyms used in this discussion.

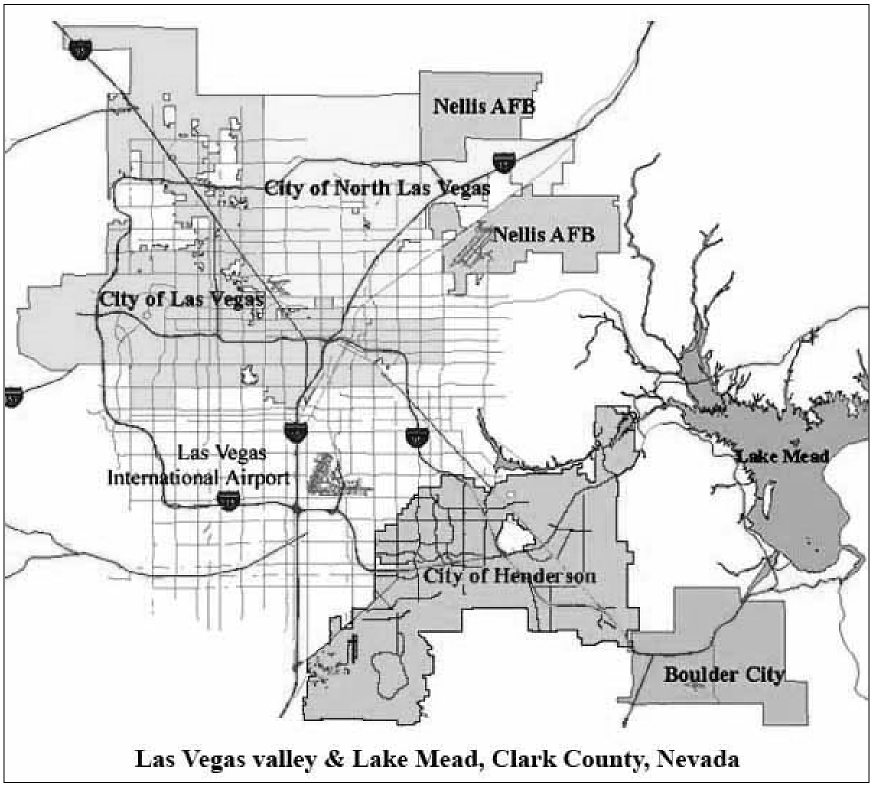

Figure 8 Greater Las Vegas Area

Table 6 Las Vegas Area Case Study Acronym List

ACRONYM	DESCRIPTION
AF	Acre Feet
AWBA	Arizona Water Banking Authority
BOR	Bureau of Reclamation
ICS	Intentionally Created Surplus
SNWA	Southern Nevada Water Authority

Although the Las Vegas area relies on three different water supply sources—groundwater, Colorado River surface water, and reclaimed water—90% of the supply comes from Colorado River surface water that leaves the area vulnerable to any supply impacts on the Colorado River. The Las Vegas area has plans to augment its supply portfolio with non Colorado River water, discussed in a later section. In this section we focus on the current supply sources and supply governance.

Groundwater

Groundwater served as the Las Vegas area's primary supply source until the early 1970s (Holmes 2010). In Nevada, use of groundwater resources is regulated by the State Engineer, and the Nevada Division of Water Resources. During the 1950s the Las Vegas area began considering expanding infrastructure to access more water from the Colorado River. However, knowing that this process would be years in the making, the State Engineer began to issue revocable groundwater well permits. The idea was to allow the area to grow knowing that groundwater resources would be over-used, but then have the ability to revoke the permits once water from the Colorado River came online (SNWA 2009b). The revocable permits were issued in addition to the permanent groundwater rights already in use. After years of groundwater overdraft in the Las Vegas Valley, the State Engineer issued an order in 1992 that, "with few exceptions, all applications to appropriate groundwater in the Las Vegas Valley that are filed after March 23, 1992 will be denied," (SNWA 2009b, p29).

Groundwater resources in Nevada follow the prior appropriation doctrine, which give priority to the water right holder with the earliest permitted use. The permanent groundwater rights held by SNWA agencies total 46,340 acre feet per year and are some of the highest priority rights in the Las Vegas Valley (SNWA 2009b). Natural groundwater recharge rates for the Las Vegas Valley are estimated to be 57,000 acre feet per year. Although municipal use of groundwater is below the natural recharge rate, there are also a variety of private groundwater users. Municipal and private use of groundwater use in the Las Vegas Valley in 2007 was around 70,000 acre feet per year, far exceeding natural recharge (SNWA 2009b).

Colorado River Surface Water

Most of Nevada's groundwater and surface water resources are managed by the State Engineer. However, management of the Colorado River is overseen by the Bureau of Reclamation and governed by a complex set of policies. Nevada is therefore subject to the laws and guidelines for use of the Colorado River as established by "The Law of the River" (Bureau of Reclamation 2010c).

Nevada's allocation of the Colorado River is 300,000 acre feet per year. However, using a system of return flow credits, the Las Vegas area is able to significantly increase its intake and consumptive use of the River. The region discharges treated wastewater to the Las Vegas Wash where it flows back to the Colorado River (SNWA 2009b). Therefore, SNWA now has annual contracts to deliver around 500,000 acre feet of Colorado River water, of which 40% (200,000 acre feet) are returned for return flow credits (Holmes 2010) and Nevada's net allocation remains at 300,000 acre feet per year. Looking ahead, Las Vegas is hoping to improve their return flow credits from 40% to 50% or 60%, which would yield huge supply increases (Holmes 2010). Although the use of return flow credits increases the ability to use Colorado River water, the flipside is that by relying heavily on one water source, the overall water supply is more vulnerable to droughts and supply restrictions than if the region had a more diverse water supply portfolio.

The priority of water rights on the Colorado River for the Lower Basin states, as determined by the "Law of the River," impacts Nevada. Nevada, along with Arizona has a lower water right priority than California and both states are subject to supply shortages according to Interim Shortage Agreements. For Nevada, the cutbacks based on Lake Mead elevations are as follows: 1) below elevation 1075 and down to elevation 1050, Nevada's allocation is cut by 13,000 acre feet; 2) below elevation 1050 and down to elevation 1025, Nevada's allocation is cut by 17,000 acre feet; 3) below elevation 1025, Nevada's allocation is cut by 20,000 acre feet. If Lake Mead's elevation nears 1000 feet, then the lower basin states and the Bureau of Reclamation will need to agree on further shortage agreements for Lake Mead elevations of below 1000 feet (Secretary of the Interior 2007).

The Las Vegas area is taking various measures in response to Colorado River water supply vulnerability, described in the following sections.

Reclaimed Water

Due to its ability to treat a large portion of its wastewater and return it to the Colorado River for return flow credits, the Las Vegas area has less of an incentive to use this treated water as reclaimed water. If instead, the region did use this treated water as reclaimed water and did not return the water to the Colorado River for return flow credits, then SNWA would not be able to increase its Colorado River intake above 300,000 acre feet per year and would have less consumptive use water available. Although the total amount of water available for use would not change, the important point is that the total amount of consumptive use would decrease. Without returning a large portion of treated wastewater to the Colorado River for return flow credits, the Las Vegas area would not be able to "extend" their consumptive use allocation.

Nonetheless, the Las Vegas area does reuse a portion of its treated wastewater locally, about 26,842 acre feet per year for the following uses: golf courses, highway landscaping, parks, power plants, schools, and construction (SNWA 2009b).

WATER STORAGE AND BACK-UP SUPPLIES

When thinking of the Las Vegas area and water storage, it is hard not to think of nearby Lake Mead with its capacity to store over 28 million acre feet per year, or two years worth of average Colorado River flow (Bureau of Reclamation 2010b). However, the Las Vegas area has a net annual allocation of Colorado River water of only 300,000 acre feet that the region can consume. During times of declared shortages on the Colorado River, this amount will decrease. So, despite the proximity to a vast reservoir, this section will focus on stored water that is legally accessible to the region on an as needed basis during time of drought or shortage. The two categories of water storage and back-up supplies that fall in this section are Water Banking and Intentionally Created Surplus (ICS).

The Las Vegas area has water storage in three different water banks. The first is locally banked water through the Las Vegas Valley Water District (which is now part of SNWA). The second is with the Arizona Water Banking Authority (AWBA), and the third is the California Water Bank. The Las Vegas Valley Water District began banking water in the underground aquifers in 1987 and to date has banked 333,639 acre feet of water (SNWA 2009b).

Agreements for Nevada to store water in Arizona's aquifers came to fruition in 2004, with Nevada able to bank 1.25 million acre feet of water through the AWBA. Nevada can withdraw 30,000 acre feet per year of that banked water in 2009 and 2010 and 40,000 acre feet per year thereafter until supplies are exhausted (SNWA 2009b). Logistically, when Nevada withdraws water from the Arizona Water Bank, the water is withdrawn from Lake Mead for Nevada and less water flows to Arizona. Arizona is able to make up for the supply decrease by accessing banked water within Arizona.

Nevada also participates in a California Water Bank, where SNWA and the Nevada Colorado River Commission entered into an agreement with Metropolitan Water District in Southern California. The agreement began in 2004 and allows Nevada to bank store unused water in California. The Bureau of Reclamation operates the agreement (SNWA 2009b). Nevada has banked 70,000 acre feet of water through 2008. To access the stored water, SNWA must give Metropolitan six months notice and they are able to withdraw 30,000 acre feet per year (SNWA 2009b).

As stated above in the Tucson section, Intentionally Created Surplus (ICS) is a mechanism for creating an intentional surplus of water in Lake Mead, accruing "credits" for the surplus, and then being able to use the "credits" to withdraw the water at a later point in time. The Las Vegas area ICS projects include: Tributary Conservation ICS on the Virgin and Muddy Rivers, Imported ICS from Coyote Spring Valley groundwater, and System Efficiency ICS from the Drop 2 Reservoir.

For Tributary Conservation ICS on the Virgin and Muddy Rivers, SNWA is able to develop up to 95% of their water rights on these rivers that pre-date the Boulder Canyon Project Act (June 25, 1929) (SNWA 2009b). SNWA began receiving credits of around 30,000 acre feet per year from this project in 2009. The method for acquiring water rights on these rivers involves active purchasing and leasing of senior agricultural rights on the rivers, which are fully appropriated and naturally flow into Lake Mead. So, water that would otherwise be used for agriculture is left in the rivers and flows to Lake Mead.

SNWA expects to begin receiving 9,000 acre feet per year of credits from Imported ICS from Coyote Spring Valley groundwater in 2010 (SNWA 2009a) Coyote Spring is located north of Las Vegas and SNWA is constructing a 15 mile pipeline which will connect to the Moapa Valley water system and then Lake Mead. The total annual amount of ICS credits that can be used from this project is 15,000 acre feet per year (SNWA 2009b). Both Tributary Conservation and Imported ICS credits can be created and used even during declared shortages. However, if the ICS credits are not used in the same year they are created then they become known as Extraordinary Conservation ICS credits. Extraordinary Conservation ICS credits can be accrued up to 300,000 acre feet, but cannot be used during times of declared shortage (SNWA 2009b).

The final ICS project under development by SNWA is the Drop 2 Reservoir System Efficiency ICS. SNWA agreed to finance a portion of the reservoir and in turn will receive 40,000 acre feet of Colorado River water per year for a total of 10 years, or 400,000 acre feet. This project expires in 2036 or when SNWA has used a total of 400,000 acre feet of water under this arrangement, whichever happens first.

SNWAs continuing ability to look for additional supplies and to store water against future shortage increases the reliability of its water supply by decreasing the likelihood of a water supply system failure during time of drought or shortage, or to bridge any gaps in supply until new sources are developed.

Rate of Water Use Growth

Since residential water use currently makes up the largest portion of water use, population growth will be the major component of future water use growth. The Las Vegas area is also a popular tourist destination and currently receives an average of 35 million tourists each year. Resorts in Las Vegas currently account for about 6.5% of water use, while not insignificant, residential water use is almost ten times higher. Although SNWA acknowledges the difficulty in long forecasting horizons, the agency is attempting to be as prepared as possible to provide a continued reliable water supply.

Current SNWA water use forecasts extend to the year 2060 and are, “based on both population projections and expected conservation,” (SNWA 2009b, p38).

Looking at population, SNWA uses population forecasts prepared by the University of Nevada Las Vegas Center for Business and Economic Research for the years 2008-2035 and extends them out to 2060. The current population of the Las Vegas area is about 2 million people and per capita water use is about 250 gallons per day. Population projections for 2035 are forecasted at 3.6 million, but SNWA recently enacted a goal to reduce per capita daily water use to 199 gallons per day by 2035. Planning scenarios incorporate population growth coupled with projected use rates in gallons per capita per day. Even with more conservation, overall water use is expected to grow and this will require SNWA to bring on additional supplies in order to maintain reliability. Using SNWAs current water use projections for 2010 and 2035 (SNWA 2009b), 2010 water use is 553,000 acre feet while 2035 water use is 739,000 acre feet, representing a growth in water use of about 34% over 25 years.

Ability to Secure New Water Sources

For the Las Vegas area the Colorado River is the largest and most important water supply source. Looking for new ways to augment the amount of water supplied to the Las Vegas area from the Colorado River will continue to be a top option; however, given the potential for supply shortages on the River coupled with a growing population, SNWA also had the foresight to explore developing non-Colorado River supply sources. Developing new water supply sources can take several years, can be costly, and is subject to political and environmental challenges. Proper planning is essential to minimize vulnerability to severe shortages and drought. This section discusses potential ideas for expanding Colorado River supplies and development of non-Colorado River supplies.

Expanding Colorado River supplies for the Las Vegas area primarily involves transfers and exchanges of water from its current use to a new use. The first of these transfers would be for the Las Vegas area to purchase or lease water rights currently used for agriculture. The second involves treating brackish water by resuming operations at the Yuma Desalting Plant, and the third is desalination. Resuming operations at the Yuma Desalting Plant and desalination are also options Arizona is considering, and could involve partnerships between the two states to share in the funding costs as well as augmented water sources. Year-long Pilot Operations at the Yuma Desalting Plant are underway to determine how efficiently the Plant can desalt the brackish water (Colorado River Project 2010b).

Currently, desalination technology is too expensive, but if technology improves and costs are reduced, then desalination may become a real possibility. As stated above in the Tucson section, potential plans to use desalination would involve construction of a desalination plant for a coastal community that is currently using Colorado River water. The community would then use desalinated water, freeing up senior Colorado River rights for the entities who fund the desalination project.

The issue with expanding Colorado River sources for the Las Vegas area, however, is that Las Vegas is already heavily dependent on the River for its water supply, which is vulnerable to drought and shortages. To diversify the region's water supply portfolio, SNWA is in the process of importing new in-state groundwater sources.

The Las Vegas Valley Water District began filing permits for un-appropriated groundwater rights in several eastern Nevada counties in 1989. After years of negotiations with the local counties over developing groundwater resources, some resources are still under negotiation or review by the State Engineer. However, currently quantifiable resources are in the neighborhood of 134,000 acre feet per year (SNWA 2009b). Part of the lengthy review process is to determine the rate of natural groundwater recharge in each of the basins, as SNWA will only have permits for the amount of groundwater that can be sustainably used.

SNWA plans to build a pipeline from eastern Nevada (Clark, Lincoln, and White Pine Counties) to bring the water to the Las Vegas area. Under normal conditions, meaning no shortage declarations on the Colorado River, SNWA is planning for these sources to be available in 2020 (SNWA 2009b). Since SNWA is able to treat its wastewater for return flow credits, these additional in-state groundwater sources will also be treated and used for return flow credits allowing SNWA to also increase its use of Colorado River (Maher 2010). So, the new groundwater sources augment the water supply directly and also indirectly through return flow credits. The exact quantity of supply increase is not yet known (Maher 2010).

Vulnerability to Climate Impacts

Since the Las Vegas area depends on the Colorado River to supply the majority of its water, the region, like Tucson, is concerned about the River's natural variability and vulnerability to climate change. As stated above for Tucson, recent reconstructions of Colorado River flow from tree rings indicate the River is vulnerable to more severe droughts than those experienced recently (Woodhouse et al. 2006). Also, climate change models indicate that temperatures in the Colorado River Basin will increase, which could have many implications on water supply and water use. Given these challenges and uncertainties, SNWA has examined their current water supply and portfolio to see where water supply reliability would stand at each shortage declaration stage on the Colorado River.

For the Las Vegas area, the concern of declining Lake Mead levels not only impacts supply through shortage declarations. Another serious concern is due to SNWAs current and planned intakes being at a Lake Mead elevation of 1,000 feet. Declines in lake elevation below 1,000 feet would greatly impair SNWAs ability to draw out of Lake Mead.

The first stage of shortage declarations takes effect when Lake Mead reaches an elevation of 1,075 feet. At this elevation SNWA will begin construction to import groundwater from Eastern Nevada, if construction is not already underway. Tributary and Imported ICS water from the Muddy/Virgin Rivers and Coyote Spring Valley will be used; however System Efficiency ICS credits from the Drop 2 Reservoir are not usable during declared shortages (SNWA 2009b). Also, any ICS credits stored as Extraordinary Conservation ICS credits cannot be used during declared shortages. Other usable supplies during declared shortage are interstate and intrastate banked resources, as well as considering further demand management strategies. These measures will continue until elevation drops reach 1,025 feet.

When Lake Mead drops below elevation 1,025 feet the Lower Basin States will meet with the Secretary of the Interior to discuss plans for maintaining Lake Mead elevations above 1,000 feet (SNWA 2009b). Also, SNWA will continue to look into possibilities for extending intake levels below 1,000 feet, and further demand management strategies will be assessed. Maintaining reliable water supplies will continue to depend on banked water and ICS credits.

If Lake Mead does reach an elevation of below 1,000 feet, Las Vegas plans to maximize its use of in-state groundwater and locally banked water, while at the same time restricting water uses to those essential for health and safety (SNWA 2009b). Natural variability of Colorado River flows coupled with climate change uncertainties pose real challenges to the reliability of the Las Vegas area's water supplies. Careful planning and monitoring is essential to minimize vulnerability to supply shortages.

Water Supply Reliability and Vulnerability: Las Vegas Self-Assessment

The SNWA Water Plan 2009 does not directly address or provide an internal assessment of supply reliability and vulnerability. However, the idea of planning for a reliable water supply that is less vulnerable than the current system of depending almost entirely on the Colorado River is apparent throughout the document. The document does not address reliability or vulnerability with respect to infrastructure outages or catastrophic events impairing the water supply, so its focus related to water supply reliability is on assuring adequate volumes of water for current and future populations, while also diversifying the supply portfolio.

Las Vegas Water Supply Reliability, Vulnerability, and Resiliency Indicators

Several quantitative indicators listed in the introduction of this Chapter are adapted and calculated for the Las Vegas area. These indicators, which are adopted from previous literature, complement and enhance the above discussions on water supply reliability, vulnerability, and resiliency in Las Vegas. Modifications from the exact definition of the indicators are made to suit the unique features of the Las Vegas area water supply, so included values are subjective, but still provide useful insight as to potential stressors on the water supply system. Unless otherwise stated, figures used in calculating the indicator values are from the SNWA Water Resource Plan 2009.

Storage Vulnerability *"Measure of region's ability to cope with extreme water events; by reservoir yield, which is approximated by consumptive demand divided by regional reservoir storage capacity (internal and upstream),"* (Lane et al. 1999, p195).

To calculate this indicator, values for consumptive demand (water use) and regional reservoir storage capacity are needed. The 2009 SNWA water resource plan lists projected 2010 annual water use at 553,000 acre feet, so we use this figure for the first part of the equation. Calculating the second part of the equation, regional reservoir storage is more challenging.

As with Tucson, we do not include Colorado River reservoir storage when calculating storage capacity. In order to assess legally available water to the Las Vegas area during times of shortage, we focus on storage in the forms of banked water and ICS. However, with many of these storage mechanisms only a portion of the total amount can be used in a given year. So, we will sum together the maximum annual amount of water available to the Las Vegas area that is stored either through interstate water banking, intrastate water banking, or ICS. This measure will provide an assessment of annual available storage versus annual water use.

Annual amounts of ICS water which are currently available, or will be within the next couple of years, includes 28,500 acre feet per year (30,000 acre feet less 5%) from the Virgin and Muddy Rivers, 9,000 acre feet per year from Coyote Spring Valley, and 40,000 acre feet per year from the Drop 2 Reservoir. Available annual banked resources include 40,000 acre feet per year from the Arizona Water Bank, 30,000 acre feet per year from the California Water Bank, and a sum of 333,639 acre feet stored in the Nevada Water Bank (SNWA 2009b). The Las Vegas area is free to withdraw any amount from its own water bank, so we include the total sum in this calculation. Summing together the maximum annual storage amount for the Las Vegas area is 481,139 acre feet.

We also assume that the storage amount can be extended by return flow credits at a rate of 4 out of every 10 acre feet diverted (Holmes 2010). Using the return flow credit rate (481,139 x 1.4) =

673,594.6 acre feet. Calculating the Storage Vulnerability Indicator we have projected 2010 annual water use (553,000 af) divided by regional storage capacity (673,594.6 af) = 0.82.

Withdrawal ratio *"Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems,"* (Lane et al. 1999, p196).

To calculate the withdrawal ratio a value for annual water withdrawals and a value of the sum of all internally generated and imported water are needed. To approximate annual water withdrawals we use 2010 projected annual water use, as stated in SNWAs Water Resource Plan, which is, 553,000 acre feet per year.

To evaluate internally generated and imported water in the Las Vegas area, we look at the total water supply based on values listed in the Water Resource Plan that are expected to be available for use in 2010. Water supply for the Las Vegas area is from the Colorado River (300,000 af); ICS from the Virgin and Muddy Rivers (28,500 af); ICS from Coyote Spring Valley (9,000 af); permitted groundwater rights (46,340 af), and reclaimed water (26,842 af). All sources except for reclaimed water are assumed to be augmented by return flow credits at a rate of 4 for every 10 diverted acre feet.

The sum of sources that can be augmented by return flow credits is (300,000 af + 28,500 af + 9,000 af + 46,340 af) 383,840 acre feet, which is multiplied by 1.4 to assess the full value with return flow credits, 383,840 * 1.4 = 537,376. Adding in reclaimed water supply (26,842 af) the previous total is equal to 564,218 acre feet per year of currently available water supply.

Calculating the Withdrawal Ratio Indicator we have annual water use (553,000 af) divided by annual supply (564,218 af) = 0.98. Annual water use is just below annual available supply for the Las Vegas area. If current supplies are close to current water use, then the current supplies will not support more water use growth without further demand management or supply augmentation.

Natural Variability *"Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of unregulated annual streamflow to the unregulated mean annual streamflow. Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes,"* (Hurd et al. 1999, p1401).

The Natural Variability Indicator is the same for Tucson, Arizona as it assesses the natural variability of river flow on the Colorado River. From the above section on Tucson, Arizona, "With the Colorado River we can look at the observed gauge record, as well as flow reconstructions from tree rings. Observed data between 1906-1995 show a coefficient of variation of 0.28, while observed and reconstructed data from 1490-1997 show coefficients of variation that range from 0.27-0.31 (Woodhouse et al. 2006)."

Groundwater Depletion *"Ratio of average groundwater withdrawals in year [i] to annual average baseflow, reflecting the extent that groundwater use rates may be exceeding recharge. Regions with high depletion rates are vulnerable to long-run changes in hydrology*," (Hurd et al. 1999, p1401).

In calculating Groundwater Depletion, values are needed for annual groundwater withdrawals and annual average baseflow. Total groundwater withdrawals (based on 2007 withdrawals) are about 70,000 acre feet per year (SNWA 2009b). Although municipal groundwater use is only 46,340 acre feet per year, total groundwater use includes not only municipal use, but also private well users. Natural groundwater recharge in the Las Vegas Valley is about 57,000 acre feet per year. Calculating the Groundwater Depletion Indicator we have total groundwater withdrawals (70,000 af) divided by natural groundwater recharge (57,000 af) = 1.23. The Las Vegas area is using groundwater in excess of natural recharge and depleting groundwater storage in the aquifer.

Reservoir System Resiliency *A measure of a reservoir system's ability to recover from drought: 1) Reservoir capacity divided by average annual inflows; 2) Annual water use or system outflows divided by average annual inflows; 3) multiply both values together.*

Since both the Las Vegas area and the Tucson AMA receive their surface water supply from the Colorado River, the Reservoir System Resiliency Indicator is the same for both metropolitan areas and we use the Colorado River reservoir system. The first value needed is total reservoir capacity. The primary storage reservoirs relevant to the Lower Basin on the Colorado River are Lakes Powell and Mead with a combined storage capacity of 54,752,000 acre feet (Bureau of Reclamation 2010a and 2010b). To find a value for average annual inflows we use the mean value calculated using the existing observed record and also the record reconstructed using tree rings, which is estimated to be about 15 million acre feet (SNWA 2010). The final value needed for the indicator calculation is average annual outflows or water use from the system. The upper and lower Colorado River Basins both have an annual allocation of 7.5 million acre feet of water. The lower basin is using their full 7.5 million acre foot allocation, but the upper basin is not. Upper basin uses are about 4.2 million acre feet per year (Bureau of Reclamation 2008). Along with upper and lower basin uses, there is also annual 1.5 million acre foot allocation for Mexico, which is delivered in full each year (Secretary of the Interior 2007).

To calculate current Colorado River water use we sum the upper basin use of 4.2 million acre feet, the lower basin use of 7.5 million acre feet, and Mexico's allocation of 1.5 million acre feet, which equals 13.2 million acre feet per year of Colorado River use.

The first equation for the indicator calculation, reservoir capacity (54,752,000 af) divided by average annual inflows (15,000,000 af) = 3.65. The second part of the equation, annual water use (13,200,000 af) divided by average annual inflows (15,000,000 af) = 0.88. Lastly, multiplying both parts together, 3.65*0.88 = 3.212.

Las Vegas Area Case Study Summary

Two of the above indicators, Natural Variability and Reservoir Resiliency are the same for both the Tucson AMA and the Las Vegas area. Natural Variability on the Colorado River is not extreme, but the size of the built reservoir system and water use from the River point to a system that is not expected to recover quickly from drought. Water withdrawals in the Las Vegas area are just shy of water supply, indicating that without stricter conservation or new water supplies there is little room for water use growth. Groundwater Depletion is a problem in the Las Vegas area as the Indicator points out that more groundwater is withdrawn than is recharged. Although the Las Vegas area does not have as much water in storage relative to annual water use as the Tucson AMA, the amount of currently accessible water is still greater than annual water use, which is a strength for Las Vegas.

Case Study: Portland, Oregon

Overview

Portland's main water source is the Bull Run Watershed. Supply infrastructure in the watershed consists of two reservoirs that are dependent on winter snowfall as well as fall and spring rains for refill. Water use in Portland is less during the fall, winter, and spring wet seasons and increases during the summer months, which is also when the reservoirs receive less rain and begin to draw down. To supplement reservoir draw down in the summer months and emergencies, or when the Bull Run supply is disrupted, Portland also relies on groundwater drawn from the Columbia South Shore Well Field (CSSWF). The well field consists of 26 wells that draw on three different aquifers. Drawing groundwater, however, is not without challenges. The main concerns with the well field include: a) adequate water in the aquifers from over extended periods of time, b) reliability of pumping and conveyance infrastructure given ongoing maintenance needs, and c) presence of manganese in water drawn from some of the wells (Portland Water Bureau, 2008).

Portland's planning horizon extends to 2028 and after looking into a number of supply augmentation alternatives, the most economically and environmentally sound alternative was to develop four currently held groundwater rights to increase supply from the CSSWF. Developing the supply was scheduled to begin in 2009 and be completed by 2028. Increased use of groundwater and continued conservation, are the preferred methods of supply augmentation for Portland at this time. As the city's needs change in the future and as population growth brings in greater financial capacities, the city may again explore additional supply augmentation alternatives.

When comparing Portland with Tucson and the Las Vegas area, perhaps the most obvious difference is climate. Average annual precipitation totals for Portland are around 36 inches (NOAA 2010c), compared with about 12 inches for Tucson (NOAA, 2010d) and less than 10 for the Las Vegas area (NOAA 2010a). However, even though the Portland area receives much more precipitation than the other two cities, Portland is still subject to similar concerns with water supply reliability: diversity and governance of supply sources, water storage and emergency back-up supplies, rate of water use growth, ability to secure new water sources, and vulnerability to climate impacts.

Like the Tucson and Las Vegas metropolitan areas, Portland is composed of a major city (the City of Portland) and several surrounding towns. Retail water supply for the City of Portland is provided by the Portland Water Bureau and the Bureau is also a wholesale water provider to several surrounding suburbs and communities. Retail water provision totals 60% of the water supplied by the Bureau and wholesale water provision totals 40% (Portland Water Bureau 2008). The Bureau has wholesale contracts with 19 water providers in the area. Table 7 lists the largest wholesale contracts (Portland Water Bureau 2008 and 2010b).

Table 7 Portland Water Bureau's Largest Wholesale Contracts

<table>
<tr><td rowspan="6">Portland Water Bureau's Largest Wholesale Contracts</td><td>Tualatin Valley Water District</td></tr>
<tr><td>Rockwood</td></tr>
<tr><td>Gresham</td></tr>
<tr><td>Tualatin</td></tr>
<tr><td>Tigard</td></tr>
<tr><td>West Slope</td></tr>
</table>

Although, the Portland Water Bureau does not serve the entire Portland metro area, its service area is the largest and most comprehensive as far as the population served and the depth of information provided by the Bureau about the area's water supply reliability. Consequently, the primary information source for this case study is the Portland Water Bureau's, "Water Management and Conservation Plan for the City of Portland, Oregon," (2008). Table 8 provides a list of frequently used acronyms.

Table 8 Portland Case Study Acronym List

ACRONYM	DESCRIPTION
ADD	Average Daily Demand
CSSWF	Columbia South Shore Well Field
MGD	Millions of Gallons Per Day
GPCD	Gallons Per Capita Per Day

DIVERSITY AND GOVERNANCE OF SUPPLY SOURCES

The two water sources in Portland are surface water from the Bull Run Watershed and groundwater pumped from the Columbia South Shore Well Field. The Bull Run Watershed is Portland's main source of water year round, while groundwater serves as an emergency back-up supply and to augment surface water supplies as needed in the summer months. Both supply sources are replenished with Pacific Northwest precipitation. However, since groundwater is naturally stored in aquifers, it is less vulnerable to annual fluctuations in precipitation than Bull Run surface water. Therefore, during dry summer months when precipitation decreases and water use increases, Bull Run supplies diminish and groundwater is used to bridge the supply gap. The supply substitution of these two sources greatly increases the reliability of Portland's water supply, compared to reliance on just one source. Figure 9 illustrates the Portland water supply system with relation to the Bull Run Watershed, groundwater wells, and surrounding wholesale communities (Portland Water Bureau 2010b).

Figure 9 Portland Water Supply System

Bull Run Surface Water

The Bull Run watershed is located in the foothills of Mt. Hood, east of the City of Portland and has a total annual water yield of about 180 billion gallons (over 550,000 acre feet) of water a year, of which around 20% is diverted to Portland for consumption. Beginning as Bull Run Lake, the water then becomes Bull Run River and is subsequently stored downstream in two reservoirs before reaching the City. The Portland Water Bureau holds Bull Run surface water rights for municipal use that are senior to all other rights (Portland Water Bureau 2008).

Although the Bureau holds all senior water rights for the Bull Run watershed, it must comply with two federal laws, which can affect its use of its rights: the Endangered Species Act and the Clean Water Act. Four anadromous fish species in the Bull Run watershed are listed as threatened under the Endangered Species Act and water temperatures under the Clean Water Act are managed to ensure, "core cold-water habitat for salmonids," (Portland Water Bureau 2008, p2-8). Complying with these laws could affect available supply, and the Bureau may need to adjust the level and timing of water releases from the two Bull Run reservoirs to ensure adequate water temperatures for fish species (Portland Water Bureau 2008).

Groundwater

Groundwater resources for the Portland Water Bureau are located on the Columbia River Flood Plain northeast of downtown Portland and consist of 26 active wells drawing on three separate aquifers (Portland Water Bureau 2008). The well field is known as the Columbia South Shore Well Field (CSSWF) and water rights are held by the City of Portland through 5 permits. Although the permits total 342 millions of gallons per day (MGD), currently only 136 MGD is developed (Portland Water Bureau 2008). Of this developed amount, pumping capacity of the aquifers for periods of around 30 days is estimated to be 102 MGD. Plans to expand groundwater pumping capacity are discussed later.

Well contamination has been a problem in the past and continues to affect certain wells. To protect groundwater supplies from urban contamination leaching into the aquifers, the City of Portland implemented measures which require, "businesses that use, store, or transport hazardous material above a certain threshold amount to implement best management practices to prevent spills on the ground," (Portland Water Bureau 2008, p2-14).

WATER STORAGE AND BACK-UP SUPPLIES

Water storage for the Portland area is composed of the reservoir system in the Bull Run watershed, while groundwater is available for emergency back-up supplies.

Bull Run Reservoirs

Unlike the multi-year storage reservoir system on the Colorado River, the Bull Run reservoirs do not have multi-year capacity and depend on winter precipitation to fill each year. In this sense, the reservoir system is resilient in that it refills each year, but is also vulnerable to shortage during warm summer months when precipitation is low and water use increases (Portland Water Bureau 2008). Two man-made reservoirs, Reservoir 1 and Reservoir 2, along with the natural Bull Run Lake, compose the available storage of the watershed.

Although Bull Run Lake is naturally occurring, a small dam maintained by the City of Portland raises the level the Lake by about 10 feet (Portland Water Bureau 2008). Total storage capacity of the Lake is about 14.8 billion gallons, but only 4.3 billion gallons are considered usable storage. An easement provision in 1997 limits releases from the lake that could compromise a complete refill of the Lake in the spring and establishes a minimum lake elevation of 3140 feet. Concurrent with the establishment of a minimum lake level, the easement also states that lake levels can be below an elevation of 3148 for only two years during a 20 year period and must be above an elevation of 3148 for all of the other 18 years (Portland Water Bureau 2008). Lake level establishments are to protect bald eagle and trout habitats (Portland Water Bureau 2010a).

Moving downstream from Bull Run Lake, the first reservoir in the watershed is Reservoir 1. Maximum capacity of Reservoir 1 is 10 billion gallons with usable capacity at 7.3 billion gallons. The closest reservoir to the Portland area is Reservoir 2, which has a maximum capacity of 6.8 billion gallons and a usable capacity of 2.6 billion gallons.

Groundwater

As mentioned above, groundwater in the Portland area is used to bridge supply gaps when the Bull Run reservoirs run low in the summer months and also as an emergency back-up supply when Bull Run water cannot be used, due usually to turbidity. Since groundwater use became available in the 1980s, the Bull Run water supply has been shut down seven times, lasting from 4 days to 27 days (Portland Water Bureau 2008).

The use of groundwater as an emergency back-up supply is reliable for the short term or about 30 days, but not long term (greater than 30-90 days) depending on water use intensity and the season. The three main limitations on the groundwater supply are limitations on, “the aquifer yields over extended periods of time, the mechanical reliability of the system, and the presence of manganese in some of the CSSWF wells,” (Portland Water Bureau 2008). To expand the reliability of groundwater as an emergency back-up supply source, the Bureau does have plans to increase supply capacity.

Rate of Water Use Growth

In order to assess water use growth, Portland Water Bureau looked at key factors influencing past water use, from 1960-2006, and developed an econometric model to look at total daily water use and also to project future water use, extending out to the year 2030. The first 20 year period of water use, from 1960-1980, were characterized by population increases, economic expansions, residential lot size increases, inefficient water fixtures, and low water rates. All of these factors lead to higher water uses. After a leveling off period in the mid 1980s, the following years were characterized by decreasing water use, in spite of population and economic growth. This was attributed to water conservation programs, smaller residential lot sizes, inclining block water rates, and new codes mandating water efficient fixtures (Portland Water Bureau 2008). Some more recent decreases in water use are also attributed to economic slowdowns and fluctuating wholesale water use.

While forecasting future water use, population growth is a primary factor. Population growth projections were provided to the Bureau by a regional governmental planning agency (Metro), which uses multifaceted planning tools for all demographic projections. Along with population, weather is another important variable in the equation. Since weather cannot be forecasted long term, the Bureau uses different past scenarios of normalized weather, and past peak seasonal water use to assess water use under the different conditions for each projection year. Using historical data based on 1967, which had the highest average daily demand (or water use) during the peak season, provides the Bureau with an idea of water use under warmer summer weather conditions (Portland Water Bureau 2008). Assessing models of high water use are important for adequate future water use planning as well as incorporating potential climate change impacts. Table 9 Shows population projections and annual average daily demand (ADD) (or average daily water use) projections based on 1) normalized annual weather conditions and 2) annual weather conditions with peak summer water use. The included years are 2010, 2020, and 2030 and water use is in Millions of Gallons per Day (MGD) (Portland Water Bureau 2008).

Table 9 Portland Water Use and Population Projections (MGD)

Year	ADD Normalized Weather	ADD Peak Seasonal Water Use	Population
2010	114.7	119.6	843,725
2020	125.4	130.9	924,920
2030	134.6	140.4	995,728

Population in the Portland Water Bureau service area is expected to increase, which will also increase water use. Annual average daily water use under normal weather conditions is expected to increase by about 17% from 2010 to 2030, and annual average daily water use with peak seasonal demands will be around 4% higher than water use under normal weather conditions (Portland Water Bureau 2008).

Ability to Secure New Water Sources

Portland has the ability and the need to develop additional water sources. There are two driving factors when assessing the need for supply expansion in Portland. The Bureau's primary reason is the increasingly important role groundwater will play in meeting future water use projections, and also needs for additional groundwater to offset Bull Run supply decreases due to: in stream flow requirements in Bull Run for fish habitat, decreases in summertime Bull Run supply due to potential climate change impacts, and turbidity impacting Bull Run.

The second reason for augmenting Portland's water supply is the need during dry years and hot, dry summers, "to meet annual average demands under higher demand weather years, projecting that the Bull Run system may be out-of-service for at least 90 days. The existing groundwater system is not capable of meeting annual average weather-normalized demands currently," (Portland Weather Bureau 2008, p5-26).

Portland has several options when considering new supply sources or augmenting existing sources. Water augmentation needs must be balanced with cost effectiveness and many options available to Portland are not currently cost effective, but may be cost effective in the future when water use growth is sufficient enough to support the financial costs. Currently the most cost effective option (which also has minimal environmental costs) is expanding the groundwater capacity of the CSSWF. Other options for supply augmentation that the Bureau considered include: development of a third dam in the Bull Run watershed; raising the dam levels on reservoirs 1 and 2 to allow for more storage; developing Bull Run groundwater, aquifer storage and recovery; and developing non-potable supplies.

Beginning in 2009 through 2028, the Bureau has plans to develop 48.54 to 53.39 MGD of its CSSWF groundwater rights, and full development of CSSWF groundwater rights held by the Bureau is expected within the next 75 years (Portland Water Bureau 2008). As stated above, the City of Portland holds rights to a total of 342 MGD of groundwater from the CSSWF, of which 136 MGD are currently developed (Portland Water Bureau 2008).

Vulnerability to Climate Impacts

Climate impacts can affect Portland's water supply through natural climatic variability and also through potential impacts of anthropogenic induced climate change. Natural precipitation variability plays an important role for the Colorado River water supplies of both Tucson and Las Vegas. For Portland, natural precipitation variability in the Bull Run watershed is currently not a pressing concern since only about 20% of the total water yield in Bull Run is used for Portland's water supply, and the resilient reservoirs refill each year (Portland Water Bureau 2008). However, increasing future water use on the Bull Run water supply primarily from population growth and fish habitat protection regulations could put greater stresses on the existing storage system. Natural temperature variability in the summer months plays a more pertinent role, as warmer summers increase water use from the water supply. Portland is currently preparing for increased water use on the Bull Run water supply by expanding the capacity of the groundwater system.

To prepare for human induced climate impacts that may go beyond any natural variability of climate seen in the past, the Portland Water Bureau not only commissioned a climate change study for the Bull Run watershed in 2002, but also stays informed of current climate science, monitors and revises long term planning, and connects with other western cities about climate change mitigation and adaptation strategies (Portland Water Bureau 2008). The commissioned climate change study on the Bull Run watershed in 2002 reported model results indicating higher average monthly temperatures in all months, but greatest in July and August. Average temperature increase of 1.5 degrees Celsius for the decade 2020 and temperature increase of 2.0 degrees Celsius for the decade 2040 were reported. Precipitation models suggested increasing winter precipitation and decreasing summer precipitation, although there was lower confidence in the precipitation models than the temperature models (Palmer and Hahn 2002). Newer climate models prepared in 2007 for the Intergovernmental Panel on Climate Change and reviewed by The University of Washington Climate Impacts Group project that temperature changes are an additional 10-20 years away than reported in 2002, and summer precipitation changes are unpredictable (Portland Water Bureau 2008).

Similar to climate change models looking at other parts of the West, precipitation models are inconsistent and unpredictable while increasing temperatures trends in the models are much more consistent. Increasing temperatures, particularly in the summer will undoubtedly impact summer water supplies in Bull Run. If groundwater supplies become insufficient at any future point to bridge the supply gap, then additional measures will need to be taken to augment supplies. These could include any of the supply enhancement options already discussed by the Bureau. Since the Bureau is aware of potential climate change impacts and monitoring long term supply plans, the odds are favorable that if supplies need to be augmented again in the future, the Bureau will be ahead of the curve.

This section looks at how the Portland Water Bureau views the reliability and vulnerability of its own water supply and provides an overview of any qualitative and quantitative measures the Bureau uses for its own assessment. Unless stated otherwise all figures used in calculating the indicator values are from the Portland Water Bureau's Water Management and Conservation Plan (2008).

To decide how to assess the reliability and vulnerability of their water supply, Portland Water Bureau looked to other utilities to find common themes of assessment. Looking at what events are most likely to affect service such as power outages, storms, earthquakes, etc., is a common theme used by utilities and adopted by the Bureau to assess their reliability and vulnerability. The events and their estimated frequency of occurrence for the Portland area are: 1) supply system breaks (main breaks, pump station outages, etc.) every 5-25 years, 2) landslides or earthquakes around every 50 years, 3) 100 to 500 year earthquakes. The Bureau states that there are few events that could affect both supply sources (Bull Run and groundwater), but that Bull Run is particularly vulnerable to turbidity impacts. In the unlikely event that both supplies were fully or partially disrupted the Bureau has some options which include off loading wholesale customers that have other supply sources and receiving water from other wholesale communities that share interconnection pipes with Portland (Portland Water Bureau 2008).

Although Portland Water Bureau does not include any calculated indicators to assess its water supply reliability or vulnerability, they do look at the ability of the current groundwater system to supply peak summer water use for a period of time greater than 90 days if Bull Run service is disrupted. Long term groundwater reliability to meet future peak summer water use is assessed by looking at estimates of MGD production capacity for 30-90 days, which is estimated at 92 MGD, but also incorporating potential groundwater supply disruptions due to routine maintenance. If routine well maintenance affects supply by 10%, then the maximum production falls to 82.8 MGD, which would not be sufficient to meet the peak summer water use (simulating peak water use using 1967 weather conditions) projected for the year 2028 (Portland Water Bureau 2008). The inability of the groundwater system to meet projected peak summer water use for planning scenarios beginning in 2028 highlights the Bureau's need to expand groundwater capacities.

Portland Water Supply Reliability, Vulnerability, and Resiliency Indicators

Calculated indicators for Portland are Storage Vulnerability, Withdrawal Ratio, Natural Variability, Groundwater Depletion, and Reservoir System Resiliency. Modifications of the indicators to suit the Portland area and water supply system are discussed with the individual indicators below. Further discussion and comparison of the indicator values for all three cities is in the next section.

Storage Vulnerability *"Measure of region's ability to cope with extreme water events; by reservoir yield, which is approximated by consumptive demand divided by regional reservoir storage capacity (internal and upstream),"* (Lane et al. 1999, p195).

To calculate the indicator we need values for annual consumptive demand (consumptive water use) and regional reservoir capacity. Portland has projections of average daily water use for 2007-2030. So, to arrive at an approximate figure for annual consumptive water use, we use average daily water use for the year 2010, which is 114.7 MGD and multiply by 365 to get an approximation for annual water use. This figure includes both retail and wholesale water use is about 42 billion gallons a year.

For reservoir capacity we use the values for usable storage in Reservoirs 1 and 2 as well as usable storage in Bull Run Lake. As mentioned above, useable storage in Reservoir 1 is 7.3 billion gallons, useable storage in Reservoir 2 is 2.6 billion gallons, and useable storage in Bull Run Lake is 4.3 billion gallons. Adding the three values together is 14.2 billion gallons. Calculating the Storage Vulnerability Indicator we have annual water use (42 billion gallons) divided by reservoir capacity (14.2 billion gallons) = 2.96.

Withdrawal ratio *"Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems,"* (Lane et al. 1999, p196).

To calculate the indicator, values are needed for annual water withdrawals and for the sum of internally generated and imported water. To approximate annual withdrawals we again use annual water use, which we calculated above using 2010 projections of daily water use, and multiplied the value by 365. The value for this first part of the equation is 42 billion gallons a year.

For the second part of the equation we need a value that represents the sum of internally generated surface and imported water, or total annual available supply. To approximate this value, we sum the median annual amount that Portland diverts from the Bull Run watershed, which is 36 billion gallons (Portland Water Bureau 2008) plus the total amount of current developed groundwater rights, which is 136 MGD or about 49.6 billion gallons annually. Adding those together, 36 + 49.6 = 85.6 billion gallons per year.

Calculating the Withdrawal Ratio is annual water use (42 billion gallons) divided by total available supply (85.6 billion gallons) = 0.49

Natural Variability *"Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of unregulated annual streamflow to the unregulated mean annual* *streamflow. Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes,*" (Hurd et al. 1999, p1401).

Unregulated streamflow of the Bull Run River, just below Bull Run Lake and before either of the reservoirs is used in the calculation of this indicator. Annual streamflow for the years 1993-2009 is available from the US Geologic Service and the mean streamflow, standard deviation, and coefficient of variation are calculated from this data. The full gauge site name is Bull Run River at Lower Flume NR Brightwood, OR (USGS 2010). The coefficient of variation for Bull Run streamflow is 0.225. Table 10 (USGS 2010) below includes the annual streamflow data points for Bull Run River and Table 11 shows the calculated statistics.

Table 10 Average Bull Run Streamflow

Year	Discharge, Cubic Ft. per Second
1993	18.5
1994	17.6
1995	24.4
1996	36.4
1997	37.5
1998	25.4
1999	30.5
2000	31.2
2001	17.4
2002	24.9
2003	23.8
2004	24.4
2005	21.7
2006	24.3
2007	26
2008	29.3
2009	30.2

Table 11 Bull Run Streamflow Statistics

Mean	Std Dev	Coeff of Var
26.088	5.862	0.225

Groundwater Depletion *"Ratio of average groundwater withdrawals in year [i] to annual average baseflow, reflecting the extent that groundwater use rates may be exceeding recharge. Regions with high depletion rates are vulnerable to long-run changes in hydrology,"* (Hurd et al. 1999, p1401).

Groundwater hydrology in the Portland area is complex due to a "paleochannel" connecting groundwater with the adjacent Columbia River (Koreny and Fisk 2000). "The Paleochannel acts as a discharge sink during low-pumping periods and a recharge source during extended pumping," (Koreny and Fisk 2000, p279). Therefore, establishing a "fixed" amount of groundwater recharge each year to use for calculating a groundwater depletion indicator is not possible. In modifying the indicator for the Portland area we use the 30 day operating capacity for the well field, which is 102 MGD. As a substitute value for baseflow we use the value for currently developed groundwater rights, which is 136 MGD.

Calculating the Groundwater Depletion Indicator is 30 day operating capacity (102 MGD) divided by developed groundwater rights (136 MGD) = 0.75. Portland comes very close to using their full developed groundwater rights during periods of high pumping. Further planned development of groundwater rights will increase pumping capacity.

An interesting point is that since groundwater is linked with the vast surface water resources of the Columbia River, increasing the use of groundwater may be an efficient way for Portland to expand supplies with less impact to the aquifers (Koreny and Fisk 2000). Current groundwater supply pumping does not have a measurable impact on Columbia River streamflow (Portland Water Bureau 2008).

Reservoir System Resiliency *A measure of a reservoir system's ability to recover from drought: 1) Reservoir capacity divided by average annual inflows; 2) Annual water use or system outflows divided by average annual inflows; 3) multiply both values together.*

Calculating this indicator for Portland we use the Bull Run watershed reservoir system. Reservoir capacity for Bull Run is the sum of Reservoirs 1 and 2, which is 16.8 billion gallons. To approximate average annual inflows we use a value for total average annual yield of the Bull Run system, which is 180 billion gallons. The final value needed for the indicator is one for annual water use from the system. To approximate the value we use Portland's median annual diversion amount, which is 36 billion gallons.

Dividing total reservoir capacity (16.8 billion gallons) by total annual yield (180 billion gallons) = 0.093. Dividing annual water use (36 billion gallons) by total annual yield (180 billion gallons) is 0.2. Multiplying the two values together = 0.0186.

Portland Area Case Study Summary

The resiliency of Portland's reservoirs is a result of a small reservoir storage and low water use with respect to the annual yield of the Bull Run watershed. With a resilient reservoir system, the City does not need as much storage, so the Storage Vulnerability Indicator is quite high when compared to the vales of Tucson or Las Vegas. The Natural Variability of Bull Run is less than the Colorado River and Portland is not using more water in general or more groundwater than is supplied.

Comparison Across Case Studies, Reflections on Indicators

This section discussed several aspects of urban water supply reliability, vulnerability, and resiliency using the cities of Tucson, Arizona, Las Vegas, Nevada, and Portland, Oregon as case studies. The varying water supply sources and system complexities of the cities provide interesting insights into the challenges of providing reliable water supply systems now, and projecting future water use. Descriptions were provided for each city on the diversity and governance of their supply sources, water storage and emergency back-up supplies, rate of water use growth, ability to secure new water sources, vulnerability to climate impacts, and how each city perceives its own water supply system reliability and vulnerability.

On a quantitative level, several indicators were calculated for each city to complement the discussion and provide further insight into water reliability, vulnerability, and resiliency status. Several challenges arise when calculating indicators, such as the geographic scope to consider, finding usable data, and deciding what components of the water supply system should be included with each indicator. For example, in Tucson, to calculate the Storage Vulnerability indicator we chose to use locally banked water to quantitatively assess Tucson's storage vulnerability. However, other relevant components that could be included in the indicator are groundwater storage reserves and Colorado River system reservoirs. Deciding what to include in an indicator is somewhat subjective and therefore, a thorough understanding of the make-up of a city's water supply system is essential in providing a context for the indicator.

As long as the indicator context is provided, as well as an understanding of the explanatory limitations of an indicator, then comparing the indicator values across cities can enhance understanding of the strengths and weaknesses of each city's urban water supply system. However, since several indicators were modified for each city, an understanding that the comparisons are not exact is warranted. If the same inputs were used to calculate indicators for each city, then an across the board comparison would be more appropriate. Using indicators to compare across cites also negates the need to convert various water volume measurements. Tucson and Las Vegas use acre feet, while Portland uses billions of gallons per day, but when a ratio or indicator is used, the calculated values do not need a conversion. Table 12 displays each city's indicators as a means to quickly see how the cities compare with each other. Increasing, or higher values indicate higher water system stress.

Table 12 Indicator Values for Tucson, Las Vegas, and Portland

	Tucson	Las Vegas	Portland
Storage Vulnerability	0.46	0.82	2.96
Withdrawal Ratio	1.06	0.98	0.49
Natural Variability	0.27-0.31	0.27-0.31	0.225
Groundwater Depletion	1.55	1.23	0.75
Reservoir Resiliency	3.21	3.21	0.0186

Note: Increasing, or higher values indicate higher water system stress for the aspect of the system being measured.

The indicators may also help cities to balance their strengths and weaknesses. Tucson and Las Vegas have a higher Natural Variability indicator value for their surface water source than Portland, but they also have a lower Storage Vulnerability indicator. A lower Storage Vulnerability indicator may help to balance out a higher Natural Variability. A large discrepancy exists between the Reservoir Resiliency of Portland contrasted with that of Tucson and Las Vegas. Portland's reservoir system would recover much more quickly from a short drought since they refill each year, but the arid climate and large water use of Colorado River water necessitate a system capable of multi-year storage.

Indicator values are dynamic and can be calculated each year as a means for municipalities to assess their own status, or report on any status changes to the general public. The City of Tucson Drought Monitoring Indicators, discussed above, provide examples of indicators reported annually. Tucson also assigns threshold values to some of their indicators, giving the indicator values more context. Given the climate and geographic differences of Portland, Las Vegas, and Tucson, assigning a single threshold value for each indicator does not provide an appropriate context, however assigning threshold values at a regional or municipal level would add value to their interpretation. Some indicators point towards water stress with or without a threshold value. A value greater than 1 for Withdrawal Ratio or Groundwater Depletion indicates water use in excess of supply, which increases a municipality's vulnerability to drought and climate change.

As cities grow and urban water use increase along with the looming uncertainties of climate change, cities will benefit from a thorough examination of their own water supply systems to assess strengths and weaknesses, which contribute to enhanced reliability or increased vulnerability. Sharing their knowledge with other western cites who face similar challenges can help create a collective pool of information to guide cities toward cost effective and reliable urban water systems that are adaptive to future challenges and uncertainties.

ECONOMETRIC ANALYSIS OF URBAN WATER TRANSACTIONS

This portion of the project research moves beyond a case study approach to investigate actual water transactions that moved water to urban areas over the period 1987-2009 in selected areas of Colorado, Nevada and New Mexico. These portions of the western U.S. were selected based on availability of adequate data on urban transactions for econometric analysis, something not available for much of the American West. These transfers do not reflect consumers purchasing retail water from a utility, but rather transactions where a utility or a municipality purchases or leases water to augment their municipal supplies. The geographic scale for the analysis is at the Metropolitan Statistical Area (MSA) level. Water transactions occurred with enough frequency in most MSAs included in the research to have a separate model for the individual MSA. However, a few models include more than one MSA in the regression. Findings suggest that water sales prices for water moving to urban areas are influenced by characteristics of the sale, such as quantity, and demographic data such as housing prices and population. The influence of drought on sales price is mixed.

With water use increasing and water supply impacts looming, municipalities face challenges to meet increasing water use, while also planning for potential future supply shortages and increased supply variability. Water markets are more developed in certain states and regions than in others. Table 13 illustrates the number of water sales in each urban area from 1987-2009 (Stratecon Inc.).

Table 13 Urban Water Sales by MSA

MSA	Colorado	Reno,	Albuquerque,

	Front Range	Nevada	New Mexico
Urban Water Sales	965	213	35

If drought and climate change lead to an increasingly arid west, and water use continue to grow, water markets may begin to mature and transactions will become more routine as water is reallocated to higher value uses. Water transactions provide an alternative to building costly new infrastructure and engaging in litigation to enhance supplies.

LITERATURE REVIEW—WATER TRANSACTIONS MODELS

A number of prior studies have developed econometric models of water transactions. All of the research reviewed in this section on U.S. markets is based, at least partially, on data from *Water Strategist*, which we also used for econometric models.

Bjornlund and O'Callaghan (2005) address implicit and explicit water irrigation prices in northern Victoria, Australia. Implicit prices reflect transactions where farmland and water are sold together, while explicit prices are simply water sold on its own for agricultural purposes. The article highlights irrigation water price sensitivity and variability to climate. Although the research is in Australia using agriculture to agriculture transfers, it suggests that the similar arid climates of the western U.S. may also experience water price sensitivities due to climate. This research builds on the ideas of Bjornlund and O'Callaghan by seeking to identify climatic sensitivities of water transfers that move water into urban areas.

Brookshire et al. (2004) examine the major water markets in Arizona, New Mexico, and Colorado. Differences across the three states in transaction costs, including monetary, legal, and time costs also play a role in market efficiency. Although these water markets are not perfectly competitive, the authors are able to gain valuable insight into water price variation using econometric analysis. Model results indicate higher prices in Colorado than in Arizona and New Mexico, while government buyers pay a lower price than agricultural or municipal buyers. Water use increases as populations become wealthier, and prices are higher in drier years.

Building off this foundation and some of the variables used in the Brookshire et al. econometric analysis, this research examines water transactions in which the buyer is always municipal in order to further identify urban water price determinants.

Brown (2006) discusses water market trends over time while also looking at the categories of buyers and sellers for sales and leases. He incorporates an econometric analysis looking at sale and lease prices separately and does not break down his models geographically, but instead includes all relevant transactions from a total of 14 states. Brown's "big picture approach" looks at western water markets as a whole and touches on a wide range of issues. However he does not test for potential problems with his models, such as endogeneity between price and quantity or heteroskedasticity. His results may be biased without thorough testing and correcting of these problems.

On a much smaller scale than Brown's western U.S. analysis, Pullen and Colby (2008) analyze water sales transactions in just one area of New Mexico, the Gila-San Francisco basin. Creating an econometric model of derived demand for sales prices, the authors model price variation by including variables relating to the characteristics of the water right. Such as the size of the transaction, location of the transaction, and the year the transaction occurred. Other exogenous variables included were the Standard Precipitation Index (SPI), the change in population, the price of copper (due to the mining industry in the area during the study period), and calf prices (due to the ranching industry). The SPI drought index measures drought conditions for varying lengths of time. The authors test four models with varying values of SPI to more accurately assess impact of drought on water sales in the regions. Using a Hausman Wu test, the authors test for and confirm the endogeneity of price and quantity in the model. R^2 values for the models are in the 0.73-0.74 range indicating that the variables explain close to 75% of the variation in price.

Pullen (2006) also analyzed urban water transactions by including water sales occurring in major urban areas in Arizona, Nevada, New Mexico, Colorado, and Utah within a single model. Significant findings in the results suggested that urban water prices were influenced by location, quantity, population change, and a trend variable indicating the year in which the transaction occurred. Although population change was significant, the sign was negative, which was not expected. The model was run twice with two different climate variables, SPI24 and SPI24 lagged six months. Although the latter was significant at the 5% level, the sign was positive, which was not expected.

Jones and Colby (2010) look at water leases, as contrasted with sales, and their econometric models provide further insight into determinates of water lease prices. The two models used in their research serve to point out similarities and differences between water leased for environmental purposes and water leased for other purposes, such as agriculture, municipal, or industrial uses. Significant results from the environmental lease model suggest that determinants of environmental lease prices include temperature, per capita income, location, whether the water was leased for a mandated or a voluntary environmental purpose, and whether the water leased was administered by a government entity. The R^2 value for the model was 0.32. Looking at the non-environmental lease model significant determinants of price include quantity, SPI, income, population, transaction number, location, land, different water uses, and whether the water leased was administered by a government entity. The R^2 value for the model was 0.45.

O'Donnell (2010) estimated lease models for California, Colorado, and New Mexico. His models were at the state level and included all leases, paired with state level demographic data. O'Donnell did include a housing price variable, but the variable did not perform well due to the large spatial scale of the data. Climate variables used included the Pacific Decadal Oscillation (PDO), temperature, and precipitation.

Econometric research on water sales and leases by Brookshire, Brown, Pullen and Colby, and Jones and Colby uses various climate and economic indicators, as well as variables inherent to the characteristics of the water right or lease contract to explain price variation. Based on the econometric modeling foundation built by these authors, this research also includes climate, economic, and water characteristic variables, as well as a two stage least squares econometric model, where endogeneity tests reject exogeneity. However, this new exploration of a specific subset of water transactions in the urban market allows for the inclusion of other economic indicators such a housing price index, and urban area population growth, as well as a new approach in including climate variables. Where possible, we included a drought index for the climate division where the water supply for the urban area originates, as opposed to previous research that included a drought index for the area where the transaction occurred. Table 14 provides a summary of recent econometric analysis on water transactions to identify differences in approach.

Table 14 Summary of Recent Water Transaction Research

Author	Time & Spatial Scale	Transaction Types & Location	Independent Climate Variables	Independent Demographic Variables	Description
Pullen 2006	1987-2004, County	Sales AZ, NM, CO, NV, UT	SPI 24 & SPI 24 lag 6	Population change; per capita income	One single, price dependent regression of sales combining several urban areas in the states listed.
Jones 2008	1987-2007 County,	Sales and Leases AZ, CA, NV, NM, UT, WY	Sales: SPI 12 lag 6 & temperature lag6; leases: SPI 6 lag 3 & temperature lag 3	Population and State level per capita income	Two price dependent regressions for sales, and two for leases combining all transactions in the listed states, but modeling

					environmental water uses separately.
O'Donnell 2010	1987-2009, State	Leases CA, CO, NM	PDO lag 6 & temperature lag 3 & precipitation lag 3	Median home prices, population, income	Three, price dependent regressions of leases, one for each state
Basta 2010	1987-2009, MSA	Sales and Leases CO, NM, NV, TX	Sales: SPI 12 lag 6; leases SPI 12 lag 3. Using 2 different climate divisions.	Housing price index; population	5 price dependent regressions of sales for individual MSAs, 1 price depended regression of lease for individual MSA, and 2 price dependent regressions, one for sales, one for leases combining 3-4 MSAs.

STUDY AREAS FOR ECONOMETRIC MODELING

Five models from different urban areas are included in this research, three in Colorado, one in Nevada, and one in New Mexico.

COLORADO

Colorado has the most active transactions market of the three states examined, in terms of the number of transactions. Sales of water moving to urban areas in Colorado are concentrated on the northern Front Range in the Denver, Boulder, Greeley, and Fort Collins areas. The three study areas in Colorado are:

Front Range The Front Range model includes the urban areas of Denver, Fort Collins, and Greeley and sums to a total of 965 observations. These areas are grouped together in one model due to their similar demographics. Also, a large number of transactions could not be separated out to the individual urban areas due to water supply entities operating in more than one of these urban areas.

Investigating the number of unique buyers and sellers included in the Front Range model reveals an active market with numerous unique buyers and sellers. The sellers are more difficult to determine as many are often just listed as an irrigator, or a farmer, without any additional information. Nonetheless, buyers and sellers in the Front Range include multiple cities, ditch companies, brokers, investors, banks, water districts, and private companies.

Boulder Boulder is a much smaller model than the Front Range, with 87 observations. Nonetheless, the urban water market in the Boulder MSA is active and competitive with several unique buyers and sellers represented in the data. Boulder demographics are different from other areas in the Colorado Front Range, in that housing prices are much higher (City-Data 2010). Only water sales that could be determined as moving water to the Boulder MSA were categorized as Boulder transactions.

CBT The Colorado Big Thompson (CBT) Project is the largest trans-mountain water diversion project in Colorado (Northern Colorado Water Conservancy District 2010). This model represents sales of CBT project water to any urban area along the northern Front Range. Through a system of dams, reservoirs, tunnels, canals, and pipes, the project moves water from the western to the eastern slope of the Rocky Mountains. Completed in 1957, the CBT Project delivers about 213,000 acre feet of water annually for irrigation, municipal, and industrial uses in Northeastern Colorado. Around 30 cities and town receive supplemental municipal water from the Project (Northern Colorado Water Conservancy District 2010). CBT project water is an important source for urban water users with a total of 940 observations in the model.

NEVADA

Reno Reno and Las Vegas are the largest urban areas in Nevada. However, only a handful of water transactions have occurred in the Las Vegas area. Consequently, Reno is the only Nevada urban area included in this research. The market is characterized by numerous sales for new development in Reno due to the Truckee Meadows Water Authority's (TMWA) Rule 7. Rule 7 requires new development that will require new water service to dedicate water rights to TMWA in the amount needed for service (Truckee Meadows Water Authority 2010). There are a total of 213 observations in the Reno model.

NEW MEXICO

Albuquerque Sales involving water moving to the Albuquerque MSA are included in this model. Urban water transactions in New Mexico occurring outside of this MSA are sparse. Water rights in New Mexico are based on the prior appropriation doctrine. All distribution and appropriation of water in the state is managed by the office of the State Engineer. The length of time to complete a water right sale in New Mexico can vary. The minimum is around three months if the transaction is not complex and there are no protests. However, for more complex transfers and for those involving protests and litigation, the process can take years (Bureau of Land Management 2010). Varying transaction and reporting times can create difficulties when using time specific variables in a model, such as climate variables.

Although, the city of Albuquerque is a major buyer of urban water in the area, urban water transactions are only a subset of the general water market in the area and several other industrial and agricultural users are also active water buyers. The number of observations is small, at just 35, but useful insights into the water market in the Albuquerque area are attained.

DATA

Data on water sale transactions come from the *Water Strategist*. The *Water Strategist* was a monthly publication compiling information on water sales and leases in the western United States, from 1987-2010. Reported transactions generally contain the following information about the water sale or lease: price per acre foot of water, total quantity, the buyer, the seller, previous use of the water, and new use of the water.

Transactions are listed by state and by month. The month the transaction is reported in the Water Strategist typically does not correspond with the month when the transaction actually was negotiated or implemented. There is usually a time lag between when parties involved in the transaction reach an agreement on price and other terms, and when the transaction is reported (Colby 1990). The typical duration of the reporting lag is unknown, but likely varies between states and transactions. Since this analysis is examining relationships between a set of independent variables and the negotiated price, we use time lags for certain independent variables to attempt to correct for the reporting lag.

Each transaction (as defined above) is one observation and contains the quantity in acre feet sold and the price per acre foot. Data from the transactions are paired with demographic and economic data at the Metropolitan Statistical Area (MSA) level, and climate data at the climate division level. Often in the West, water supply originates as precipitation in a different climate division from where the water is being transferred. So, we include climate data, the SPI, from the climate division corresponding to where the water supply originates.

VARIABLE DESCRIPTIONS

The following variables are used in all models:

Lnprice The natural log of price per acre foot of water for either sales or leases for each transaction. All prices are adjusted for inflation using the Consumer Price Index and are in 2009 real dollars. Lnprice is the dependent variable in all regressions.

Quantity/Qhat Quantity in acre feet per transaction, or the predicted value of quantity in acre feet for each transaction from stage one instrumental variable (IV) regressions. We expect Quantity/Qhat to have a negative sign indicating a downward sloping demand curve and the inverse relationship between price and quantity for normal goods. However, when the sign on quantity is positive, this could indicate increasing transaction costs stemming from higher levels of objections to a larger transfer (Colby 1990).

Adj_housing Conventional Mortgage Home Price Index (CMHPI) (Freddie Mac 2010a) adjusted for inflation using the Consumer Price Index to reflect 2009 prices. The CMHPI is released quarterly, so quarterly values were interpolated using PROC EXPAND in SAS to monthly values. The CMHPI is compiled by Freddie Mac and, "is based on mortgages that were purchased or securitized by Freddie Mac or Fannie Mae since January 1975. These mortgages are "conventional" in their financing: they are not insured or guaranteed by any federal government agency… the index is based on mortgages for single unit residential houses only," (Freddie Mac 2010b). The CMHPI is used as a variable over other accessible housing market data, such as median home values from the National Association of Realtors, since the data is available for both the number of years needed (1987-2009) and the spatial scale of Metropolitan Statistical Area (MSA). We expect the sign of adj_housing to be positive since housing prices are a strong indicator of the status of the local economy.

SPI12_L6 A six month lag of the 12 month Standardized Precipitation Index (SPI). The SPI is a drought measurement index based on precipitation. The range of the SPI is continuous between -3 to +3 with negative values corresponding to drier than normal conditions and positive values to wetter than normal conditions (National Climate Data Center 2010b). The SPI is calculated for different time scales, from one month to 24 months, to measure short term and long term climate conditions. (National Climate Data Center 2010a) SPI12 picks up drought conditions over the past year, and the time lags attempt to capture any reporting lags from when the transfer occurred to when the transfer was reported in the *Water Strategist*.

The SPI climate variable used in all Colorado models is from Colorado's climate division 2 (NOAA 2010b), where Colorado's primary water supply source originates in the northern Rocky Mountains as snowpack. The SPI climate variable used in the Albuquerque model is from Colorado's climate division 5. In this climate division, a primary water supply source originates in the southern Rocky Mountains, which are the headwaters of a main water supply, the Rio Grande, for the Albuquerque region. The SPI climate variable used in the Reno model is from California's climate division 3. This climate division represents a main source of water for the Reno area originating as snowpack in the Northern Sierras.

We expect all SPI variables to be negative since drier conditions and water scarcity in the area in which supplies originate, can lead to higher water prices.

Variables used in certain models:

Pop_exp Total population by MSA (Real Estate Data Center 2010). Annual data was available, and the values were expanded to monthly values using PROC EXPAND in SAS. We expect the sign on pop_exp to be positive since water demand increases with population and higher demand leads to increasing prices. Pop_exp is not used in all models due to collinearity issues.

Sup_dummy A dummy variable with a value of 1 if the original water use was for agricultural uses, 0 otherwise. We expect the sign to be negative since agricultural water is a lower value use than other uses such as industrial, environmental, or municipal uses. Therefore, a municipality purchasing or leasing water is likely to pay less if the water was previously used in the agricultural sector, than if the water was used in another sector .

CBT_dummy A dummy variable in the Boulder model only taking a value of 1 if the transfer was Colorado Big Thompson (CBT) Project water and 0 otherwise. We expect this variable to be positive, as CBT prices are generally on the higher end of water sales prices in Colorado. The CBT market is highly developed and competitive, so buyers may be willing to pay more for CBT water if transaction costs are lower, and there is an ease of entry into the market.

Descriptions of instrumental variables used in stage one regressions for the models in which price and quantity are endogenous are in the appendix.

METHODOLOGY

Each model is set up with price as the dependent variable and a semi-log functional form is used for all models. Box Cox transformation results for each model indicate that the natural log of price improves model fit over a linear form. In calculating the marginal effects, since all models are in semi-log functional form, all non dummy variable parameter estimates represent the percent change in water price per acre foot given a unit change in the corresponding variable. If the variable is a dummy variable, then the percent change in water price is calculated as $e^{B}-1$, where B is the dummy variable parameter estimate. The marginal effects for all models are displayed below in the next section.

We conduct endogeneity and heteroskedasticity tests on each model. Endogeneity between price and quantity is a potential problem. If quantity is not independent from the disturbance term, then OLS estimators are biased and inconsistent (Johnston and DiNardo 1996). We use a Hausman Wu test to test for endogeneity between price and quantity, with the null hypothesis assuming exogeneity. If we reject that quantity is exogenous, then a Two Stage Least Squares (2SLS) model is used. However, if we fail to reject exogeneity, then we use an OLS model since 2SLS estimators are not as efficient as OLS estimators if all independent variables are exogenous (Wooldridge 2000).

In estimating the 2SLS models we regress all exogenous variables, plus additional instrumental variables, on quantity in the first stage. Then, we use the predicted values of quantity in place of the actual values of quantity in the second stage. In generating the correct standard errors for the 2SLS models, sigma squared is calculated using the parameter estimates in the second stage regression, but the actual values of all the variables. Of the five models in this study, exogeneity is rejected in the Front Range, CBT, and Reno models, all other models are OLS.

In testing for heteroskedasticity we use White's test. If homoskedasticity is rejected then standard errors are corrected to reflect robust standard errors. Of the five models in this study homoskedasticity is rejected in two models, Boulder and Albuquerque.

Multicollinearity is investigated for each regression using Variance Inflation Factor (VIF) and tolerance levels. We examined which variables were the cause of collinearity and adjusted the models accordingly. Per capita income was originally included in all models, but subsequently removed due to collinearity issues in all models. After removing income, the Front Range and Boulder models still exhibited collinearity, so the population variable was removed from both models. The CBT dummy variable was also removed from the Front Range model. Removing these variables resolved the collinearity.

ECONOMETRIC RESULTS

Regression results for each model are found in Appendix A. Although each water market is unique and the factors influencing water prices can differ across regions and be quite localized, some consistent patterns can still be observed after examining all regression results. For all models, the housing price index variable, adj_housing, is positive and statistically significant. The importance of including adj_housing in the regressions is that it may be a more appropriate demographic variable to incorporate than income. Since houses and water are both legally considered property, fluctuations in the urban housing market may have a stronger relationship with fluctuations in the urban water market.

Population is also a strong variable across models. The population variable was removed from the Front Range and Boulder models due to collinearity with the housing index variable. However population is positive and significant in every other model. Since the per capita income variable was removed from all models due to collinearity with either the population or the housing index variable, we are not able to discuss how per capita income influences urban water prices.

Although the SPI variable is negative, as expected, in all models except Reno, it is significant only in the Colorado models. For Colorado, this suggests that drought in the climate division where a significant source of their water supply originates increases urban water prices. However, no determination can be made about the effect of drought on urban water prices in the Albuquerque or Reno MSAs.

Determining the quantitative effects of drought on urban water prices is challenging. First, how quickly drought affects urban water transactions is likely very localized, so the SPI 12 may be a better fit for one region, while the SPI 24 or SPI6, etc., another. The reporting time lag discussed in previous sections is also an issue. Transactions may be reported several months after the actual transaction occurred, and some may not be reported many months after successful price negotiations if the transaction was met with any protest and ensuing delays.

Previous empirical research on water transactions, which included a drought variable, used a drought variable corresponding to the climate division where the water was being transferred for a new use, while this research used drought variables corresponding to the location of an MSAs water supply origin. Including an SPI variable from more than one climate division in a regression could potentially provide more information on the effects of drought on urban water prices. The main problem in doing so is that an interaction term would need to be included in the regression as well. The scaling of the SPI from -3 to +3 does not permit creating a multiplicative interaction term. So, at this point, including more than one SPI variable in a regression is not practicable.

Also, in some regions, urban water prices may be more influenced by economic and demographic factors, such as housing prices and population, than drought at this point in time. That said, drought may play an increasingly important role as municipalities plan for population growth, severe droughts, and climate change.

Table 15 compiles the marginal effects of each model.

Table 155 Marginal Effects and Significance for CO, NM, and NV Models

State:	**Colorado**			**New Mexico**	**Nevada**
Model:	**Front Range**	**Boulder**	**CBT**	**Albuquerque**	**Reno**
Variables					
CBT_dummy	N/A	1.5007***	N/A	N/A	N/A
sup_dummy	N/A	NA	N/A	-0.19785**	-0.2074
adj_cmhpi	0.01388***	0.0105***	0.0128***	0.0061**	0.0062***

pop_exp	N/A	N/A	0.0000002***	0.000005***	0.000005***
trans_freq	0.00084	-0.0343**	0.0011	0.0348	-0.0033
SPI12_L6	-0.07445***	-0.0828*	-0.1158***	-0.0017	0.0754*
Qhat/quantity	-0.00064***	0.0004***	-0.0071***	0.00002	-0.0002***
**** significant at 1%* *** significant at 5%* ** significant at 10%*					

Econometric Models—Conclusion, Policy Implications, Future Work

Note – section is duplicative as it was drawn from several prior papers, needs to be trimmed and streamlined

This research empirically examines prices for urban water transactions to gain a clearer understanding of price determinants in several markets in the western U.S. As previous research results have found, prices for water intended for municipal use are higher than water prices intended for agricultural use (Jones 2008 and Pullen 2006). Building from these results, this research empirically examines prices for municipal (or urban) use to gain a clearer understanding of price determinants in several markets in the western U.S. Independent variables in the models include economic and demographic variables, variables that are characteristics of the particular sale or lease, and climate variables. Although the results of the climate variables are mixed in the analyses, the influence of climate on water supply reliability is an increasingly important issue with many utilities incorporating climate change vulnerability assessments into their long term water reliability planning.

Different spatial scales have been used in previous research on water transactions, such as the state level and the county level, and often several states or regions were included in a single regression. In this research, several models with data from a single MSA are used. In examining previous results, as well as our own, smaller spatial scales with data on an individual market generally perform better than those at larger spatial scales and those including more than one area. Econometric research on water transactions is often limited by the number of transactions occurring on a smaller spatial scale. However, as more transactions occur over time, many models could be improved as more data becomes available.

Municipalities or other entities looking to purchase water to augment current supplies would likely benefit if they purchased in the current economic climate. Water prices, following the trend of housing prices, are low compared to prices seen just a few years ago. Populations are expected to continue growing, placing ever higher demands on municipal water. Also, current drought conditions are affecting urban water prices in certain areas, so any future climate change impacts that exacerbate drought conditions, would also be expected to increase urban water prices. If long term climate and climate change modeling techniques improve to a point where forecasts have a significant impact on water management, then forecasts of near term drought could also increase urban water prices if droughts can be accurately anticipated.

In the Front Range, Boulder, CBT, Albuquerque, and Reno models we use the SPI variable that corresponds to the climate division where much of the water supply for the urban area originates. Including an SPI variable from more than one climate division in a regression could potentially provide more information on the effects of drought on urban water prices. The main problem in doing so is that an interaction term would need to be included in the regression as well. The scaling of the SPI from -3 to +3 does not permit creating a multiplicative interaction term, so, at this point we are not able to include more than one SPI variable in a regression. If the SPI could be rescaled or recoded, an interaction term may be able to be used.

Identifying which climate division SPI variable has an effect on urban water prices is clearer in some models than in others. In the Colorado models, the SPI variable from the climate division representing where much of their water supply originates is negative, and significant in all three models. We also ran the Colorado models with a different SPI variable, that which represents the climate division where the water is used. The SPI variable in the latter case is not significant in any of the three models. Both SPI variables are a 12 month SPI lagged 6 months. So, for Colorado, drought the climate division representing where significant portions of their water supply originate increases urban water prices, while drought in the climate division representing where the water is used has an insignificant effect.

Results from the empirical part of this research suggest that water markets are localized, with models encompassing a smaller geographic region generally performing better than those combining several regions into one larger model at the state level. Continuing to refine the geographic areas of specific water markets and find corresponding independent variables could lead to improved model performance. This is also applicable when looking for better instrumental variables. Instrumental variables used for this research were not always strong predictors of quantity, so a further refinement could also make a difference in correctly identifying endogeneity. Also, with respect to endogeneity, any observed patterns in markets where endogeneity tests consistently reject exogeneity or fail to reject endogeneity could be explored further.

Future work could also investigate the use of climate and drought variables in each model to see if using different time scales and lags for different models could reveal any insight as to how long term versus short term drought affects different water markets. For example, we chose to use the same SPI for each model with just a different time lag sales and leases. Our thoughts were to have a base for comparison across models. However, using different SPIs and lags for each model may be more fitting due to the local relationships between drought and water supply.

Other potential sources of price variation that could be explored include: looking at seasonal price variations and economic recession cycles. Seasonal prices variations could vary from region to region, so looking into seasonal price variation at a localized level would most likely illuminate any seasonality in urban water prices. Economic recession cycles may also impact urban water prices. This research explored the positive relationship between urban water prices and housing prices, and since housing prices are often closely related with regional economic conditions, future work could explore previous recessions and review any impact on past water prices.

Although we did a preliminary investigation into the number of buyers and sellers in each individual urban area, more work could be done to determine if any market power influences exist that affect water prices. Major buyers and sellers of water could negotiate special prices, as could pairs of buyers and sellers who routinely negotiate transfers together (Emerick 2007). An imbalance in the size of buyers or their water needs could also be investigated as a source of price variation. If a large water provider is in direct competition with a smaller water provider, then the water could be worth more to the small water provider than the larger water provider depending on the percentage increase the purchase would have on augmenting existing supplies. If the percentage is greater for the smaller provider, they may be willing to pay much more to secure the new supplies than another competitor.

Further development and refinement of indicator calculations and values for assessing urban water supply reliability, vulnerability, and resiliency could enhance the discussion and strengthen their quantitative application. Threshold values for indicator values could be addressed to provide a richer context about the status of the region’s water supply. Also, data availability permitting, indicator values could be calculated for previous years, and into the future. This could allow for the indicators to be used as monitoring tools for changes in components of supply reliability, vulnerability, and resiliency. If several years of indicator values are developed, these values could then be used in future regression analysis as well.

Until climate models attain a finer geographical resolution that is more useful for utilities, utilities have other options for assessing their own water supply vulnerability to climate change. Collaboration to identify key indicators would help utilities clarify their own strengths and weaknesses and, if calculated on an annual basis, are useful monitoring tools for measuring progress in alleviating any areas of water supply reliability weakness.

APPENDIX A: REGRESSION RESULTS FOR REGIONAL MODELS

NOTE: As explained in the text, some models required estimation by 2SLS. For others, OLS was the most appropriate estimation method.

FRONT RANGE MODEL

Front Range List of Variables

Variable	Description
adj_cmhpi	housing price index by MSA adjusted for inflation
trans_Freq	the number of sales in each year
COSPI12_DIV2_L6	SPI 12 lag six for CO climate division 2 where water supply is located for front range
Qhat	predicted quantity per transaction in acre feet

Front Range Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	10273.4	7369.19	105.22	28476.78
Quantity	111.5	698.4	0.5	13000
adj_cmhpi	237.68	47.38	158.97	302.85
trans_Freq	52.8	22.8	10	90
COSPI12_DIV2_L6	-0.05	0.86	-2.89	1.54

Front Range 2SLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.64662	0.17319	32.6	<.0001
adj_cmhpi	1.388%	0.01388	0.00054	25.59	<.0001
trans_Freq	0.084%	0.00084	0.00105	0.8	0.4246
COSPI12_DIV2_L6	-7.445%	-0.07445	0.02319	-3.21	0.0014
Qhat	-0.064%	-0.00064	0.00020	-3.2	0.0014
n = 965					
adj R^2=0.596					

BOULDER MODEL

Boulder List of Variables

Variable	Description
CBT_dummy	dummy variable equal to 1 if the sale is CBT water, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
trans_Freq	the number of sales in each year
COSPI12_DIV2_L6	SPI 12 lag six for CO climate division 2 where water supply is located for front range
quantity	quantity per transaction in acre feet

Boulder Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	9764.24	7774.89	697.40	23137.39
CBT_dummy	0.74	0.44	0	1
adj_cmhpi	281.7	66.4	174.9	363.7
trans_freq	6.29	3.66	1	13
COSPI12_DIV2_L6	-0.11	0.95	-2.26	1.54
Quantity	132.34	462.78	0.7	3500

Boulder OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.2538	0.3345	15.71	<.0001
CBT_dummy	150.07%	0.9166	0.1693	5.41	<.0001
adj_cmhpi	1.05%	0.0105	0.0007	15.48	<.0001
trans_freq	-3.43%	-0.0343	0.0147	-2.33	0.0223
COSPI12_DIV2_L6	-8.28%	-0.0828	0.0491	-1.69	0.0958
Quantity	0.04%	0.0004	0.0001	5.30	<.0001
n = 87					
adj R^2=0.819					

CBT MODEL

CBT List of Variables

Variable	Description
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
COSPI12_DIV2_L6	SPI 12 lag six for CO climate division 2 where water supply is located for front range
Qhat	predicted quantity per transaction in acre feet

CBT Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	10894.8	7441.35	1100	28476.78
adj_cmhpi	243.89	50.04	158.97	361.18
pop_exp	1944974	499920	220489	2496205
trans_freq	53.9	23.3	2	91
COSPI12_DIV2_L6	-0.087	0.854	-2.89	1.54
Quantity	40.29	98.32	0.5	1246

CBT 2SLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.7111	0.2840	20.11	<.0001
adj_cmhpi	1.276%	0.0128	0.0005	23.31	<.0001
pop_exp	0.00002%	0.0000002	0.0000001	3.33	0.0009
trans_freq	0.115%	0.0011	0.0012	0.96	0.3361
COSPI12_DIV2_L6	-11.581%	-0.1158	0.0289	-4	<.0001
Qhat	-0.705%	-0.0071	0.0019	-3.62	0.0003
n = 940					
adj R^2=0.5206					

ALBUQUERQUE MODEL

Albuquerque List of Variables

Variable	Description
sup_dummy	dummy variable equal to 1 if the supply comes from agriculture, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
COSPI12_DIV5_L6	SPI 12 lag six for CO climate division 2 where water supply is located for New Mexico
Quantity	quantity per transaction in acre feet

Albuquerque Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	3402.6	2032.1	1154.6	8000
sup_dummy	0.8	0.4	0.0	1
adj_cmhpi	188.80	21.26	162.31	245.82
pop_exp	671116	90525.9	562268	847485.4
trans_freq	2.6	1.35473	1	5
COSPI12_DIV5_L6	0.492	0.980	-1.920	2.150
Quantity	147.6	156.8	2.2	680.4

Albuquerque OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		3.3048	0.4019	8.22	<.0001
sup_dummy	-19.7850%	-0.2205	0.1070	-2.06	0.0487
adj_cmhpi	0.6050%	0.0061	0.0024	2.51	0.0182
pop_exp	0.0005%	0.000005	0.000001	6.34	<.0001
trans_freq	3.4840%	0.0348	0.0279	1.25	0.2215
COSPI12_DIV5_L6	-0.1680%	-0.0017	0.0509	-0.03	0.9738
quantity	0.0016%	0.00002	0.0003	0.05	0.9622
n=35					
adj R^2=0.8592					

RENO MODEL

Reno List of Variables

Variable	Description
sup_dummy	dummy variable equal to 1 if the supply comes from agriculture, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
CASPI12_DIV3_L6	SPI 12 lag six for CO climate division 2 where water supply is located for Reno
Qhat	predicted quantity per transaction in acre feet

Reno Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	14108.3	11966.8	797.0	47887.7
sup_dummy	0.00469	0.06852	0	1
adj_cmhpi	260.43	65.30	175.16	363.29
pop_exp	362938	51511.9	233036	418792.8
trans_freq	17.3	6.7	1	27
CASPI12_DIV3_L6	-0.15	1.07	-2.01	1.91
Quantity	231.6	458.9	0.15	3487

Reno OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.7027	0.3174	17.97	<.0001
sup_dummy	-20.7434%	-0.2325	0.5945	-0.39	0.6961
adj_cmhpi	0.6230%	0.0062	0.0012	5.3	<.0001
pop_exp	0.0005%	0.000005	0.000001	4.38	<.0001
trans_freq	-0.3280%	-0.0033	0.0104	-0.32	0.7529
CASPI12_DIV3_L6	7.5440%	0.0754	0.0420	1.8	0.0738
quantity	-0.0244%	-0.0002	0.0001	-2.77	0.0062
n=213					
adj R^2=0.5608					

APPENDIX B: INSTRUMENTAL VARIABLE DESCRIPTIONS

frminc_lag12 Annual total farm income at the state level lagged 12 months. We lag the variable 12 months since farm income from the previous year is more likely to have an effect on the quantity of water sold out of agriculture in the current year. Also, at the time of this research, data was not available for the most current year (United States Department of Agriculture 2010).

SPI24_L6 We use another SPI variable, which reflects longer term drought conditions, to account for any long term drought conditions that may affect decisions on selling or leasing water. This variable is a 24 month drought variable and measures drought conditions over a two year period. The SPI drought variables listed previously are all SPI 12 variables and capture drought conditions over a one year period. This longer term SPI variable is also from the climate division representing where water supply originates, and is also lagged 6 months to account for any reporting lags.

Groundwater OR sup_dummy We use the sup_dummy variable for several models in the second stage regression, so for those models where sup_dummy is a variable used in the second stage, we use groundwater as an instrumental variable in the first stage. For models that do not include a sup_dummy variable in the second stage regression, we use the sup_dummy variable as an instrumental variable. Groundwater is a dummy variable taking a value of 1 if the water transferred is groundwater, 0 otherwise. The sign on groundwater could vary between locations depending on the quality and infrastructure of groundwater in the area. This variable is only used in certain models where groundwater use is prevalent. As stated above sup_dummy is a dummy variable with a value of 1 if the original water use was for agricultural uses, 0 otherwise.

REFERENCES

Arizona Department of Water Resources (ADWR). “Arizona Water Atlas: Volume One.” Appendix G. http://www.adwr.state.az.us/AzDWR/StatewidePlanning/WaterAtlas/documents/appendix_g.pdf. Accessed October 2010a.

ADWR. “DRAFT Demand and Supply Assessment: Tucson Active Management Area.” http://www.azwater.gov/AzDWR/WaterManagement/Assessments/documents/FINALTAMAASSESSMENT.pdf. Accessed July 2010b.

ADWR. “Drought Preparedness in Arizona.” http://www.azwater.gov/azdwr/StatewidePlanning/Drought/default.htm. Accessed October 2010c.

ADWR. “2009 Long Term Storage Account (LTSA) Summary.” http://www.azwater.gov/azdwr/WaterManagement/Recharge/documents/LTSACompilation_2009inprogress.pdf. Accessed August 10, 2010d.

ADWR. “Recharge Credits and Accounting.” http://www.azwater.gov/azdwr/WaterManagement/Recharge/RechargeCreditsandAccounting.htm. Accessed August 10, 2010e.

Barker, J. “Aquifers of the Tucson Active Management Area.” http://academic.emporia.edu/schulmem/hydro/TERM%20PROJECTS/2009/Barker/John.htm. 2009. Accessed August 12, 2010.

Basta , Elizabeth. “Urban Water Supply Reliability and Climate Change”, M.S. Thesis, Department of Agricultural and Resource Economics, The University of Arizona, 2010.

Bjornlund, H., and B. O’Callaghan. “A Comparison of Implicit Values and Explicit Prices of Water,” *Pacific Rim Property Research Journal*, 11 no. 3 (2005):316-331.

Brewer, J, R. Glennon, .A. Ker., and G. Libecap. "Transferring Water in the American West: 1987-2005." *University of Michigan Journal of Law Reform*, 40 no. 4 (2006-2007):1021-1053.

Brookshire, D.S., B. Colby, M. Ewers, and P.T. Ganderton. "Market Prices for Water in the Semiarid West of the United States." *Water Resources Research*, 40 (2004).

Brown, T. C. "Trends in Water Market Activity and Price in the Western United States." *Water Resources Research, 42* (2006).

Bureau of Land Management (BLM). "Western States Water Laws." http://www.blm.gov/nstc/WaterLaws/colorado.html. Accessed November 2010.

Bureau of Reclamation. "Provisional Upper Colorado River Basin Consumptive Uses and Losses Report 2006-2010." 2008, http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html. Accessed November 2010.

Bureau of Reclamation. "Glen Canyon Dam Quick Facts." http://www.usbr.gov/uc/rm/crsp/gc/gcFacts.html. Accessed October 2010a.

Bureau of Reclamation. "Hoover Dam Frequently Asked Questions and Answers." www.usbr.gov/lc/hooverdam/faqs/lakefaqs.html. Accessed July 2010b.

Bureau of Reclamation. "Law of the River." http://www.usbr.gov/lc/region/pao/lawofrvr.html. Accessed August 2010c.

Bureau of Reclamation. "Reclamation, Municipal Agencies launch Yuma Desalting Plant Pilot Run. celebrate Drop 2 Storage Reservoir Project." April 28, 2010d. http://www.usbr.gov/newsroom/newsrelease/detail.cfm?RecordID=32341. Accessed September 17, 2010.

Central Arizona Project (CAP). "Project ADD Water," http://www.projectaddwater.com/. Accessed August 2010a.

CAP. “Public Board Meeting.” October 7, 2010b.

City of Tucson Water Department. “Reclaimed Water System Status Report – 2007.” http://www.ci.tucson.az.us/water/docs/rwssr-07.pdf. Accessed December 2009.

City of Tucson Water Department. “Water Plan: 2000-2050, Update to Long Range Water Plan.” 2008. http://www.ci.tucson.az.us/water/waterplan-2008.htm. Accessed March 2009.

City of Tucson Water Department. “Annual Drought Monitoring Report.” 2009. http://www.ci.tucson.az.us/water/docs/annual-drought-report-09.pdf. Accessed February 2010.

City of Tucson Water Department. “Current Water Rate Schedules.” http://www.ci.tucson.az.us/water/docs/rates.pdf. Accessed August 2010.

City of Tucson and Pima County. “Phase Two Final Report: Water and Wastewater Infrastructure, Supply and Planning Study.” City of Tucson and Pima County Cooperative Project. 2009.

City-Data. “Boulder, Colorado.” http://www.city-data.com/city/Boulder-Colorado.html,.Accessed November 2010.

Colby, B. G. “Transactions Costs and Efficiency in Western Water Allocation.” *American Journal of Agricultural Economics*, 72 (1990):1184-1192.

Colorado River Project. “Drop 2 Storage Reservoir Nearing Completion.” *River Report.* Fall 2010a.

Colorado River Project. “Yuma Desalting Plant Now in Operation.” *River Report.* Fall 2010b.

Emerick, K. “Upstream Market Power in Water Transfers.” MS thesis. University of Arizona. 2007.

Forensic Science Center. “Facts About the City of Henderson.” http://www.hendersoncrimelab.com/about_henderson.html. Accessed October 2010.

Freddie Mac. “CMHPI Data: MSA (1975-current).” http://www.freddiemac.com/finance/cmhpi/. Accessed March 2010a.

Freddie Mac. “CMHPI Frequently Asked Questions.” http://www.freddiemac.com/finance/cmhpi/faq.htm#whatMean. Accessed April 2010b.

Garfin, G., M.A. Crimmins, and K.L. Jacobs. “Drought, Climate Variability, and Implications for Water Supply and Management.” *In Arizona Water Policy: Management Innovations in an Urbanizing, Arid Region.* eds. B.G. Colby and K.L. Jacobs, 61-78, Washington, DC, Resources for the Future Press, 2007.

Hashimoto, T., J.R. Stedinger, D.P. Loucks. 1982. “Reliability, Resiliency, and Vulnerability Criteria for Water Resource System Performance Evaluation.” *Water Resources Research*, 18, no. 1 (February 1982):14-20.

Holmes, R. Deputy General Manager Engineering/Operations. Southern Nevada Water Authority. Personal Interview. February 18, 2010.

Hurd, B., R.J. Leary, and J. Smith. “Relative Regional Vulnerability of Water Resources to Climate Change.” *Journal of the American Water Resources Association*, 35, no. 6 (1999).

Johnston, J., and J. Dinardo. *Econometric Methods.* 4th ed. McGraw-Hill/Irwin. 1996.

Jones, L. “Environmental Water Markets.” MS thesis. University of Arizona. 2008.

Jones, L., and B.G. Colby. “Weather, Climate and Environmental Water Transactions.” *Weather, Climate and Society*, 2 (May 2010).

Koreny, J.S., and T.T. Fisk. “Hydraulic Continuity of the Portland Basin Deep Aquifer System.” *Environmental & Engineering Geoscience*, 4 no. 3 (Summer 2000).

Lane, Melissa E., Kirshen, Paul H., and Vogel, Richard M. “Indicators of Impacts of Global Climate Change on U.S. Water Resources,” *Journal of Water Resources Planning and Management*, (July/August 1999):194-204.

Lang, Jessica. “Analysis of Seven Qualities that Affect the Reliability, Resiliency and Vulnerability of Water Supply Systems of Cities in the Front Range of Colorado,” Unpublished (2003).

Maher, Thomas. Senior Resource Analyst, Southern Nevada Water Authority. Telephone Interview. February 26, 2010.

National Climate Data Center (NCDC). “Index of /pub/data/cirs,” http://www1.ncdc.noaa.gov/pub/data/cirs/. Accessed March 2010a.

NCDC. “US Standardized Precipitation Index.” http://lwf.ncdc.noaa.gov/oa/climate/research/prelim/drought/spi.html, Accessed October 2010b.

National Oceanic and Atmospheric Association (NOAA). National Weather Service Forecast Office. “Climate of Las Vegas, NV.” http://www.wrh.noaa.gov/vef/climate/index.php. Accessed September 2010a.

NOAA. “Climate Prediction Center: Climate Divisions with Counties.” http://www.cpc.noaa.gov/products/analysis_monitoring/regional_monitoring/CLIM_DIVS/states_counties_climate-divisions.shtml. Accessed March 2010b.

NOAA. National Weather Service Forecast Office. “Portland Airport, Oregon: Normals, Means and Extremes.” http://www.wrh.noaa.gov/pqr/climate/pdx_clisummary.php. Accessed September 2010c.

NOAA. National Weather Service Forecast Office. “Tucson, AZ.” http://www.wrh.noaa.gov/twc/climate/tus.php. Accessed September 2010d.

Northern Colorado Water Conservancy District (NCWCD). “Colorado Big Thompson Project.” http://www.ncwcd.org/project_features/cbt_main.asp. Accessed November 2010.

O'Donnell, M. "Innovative Water Supply Reliability Arrangements." MS thesis, University of Arizona. 2010.

Palmer, Dr. R.N., and M. Hahn, Margaret. "The Impacts of Climate Change on Portland's Water Supply: An Investigation of Potential Hydrologic and Management Impacts on the Bull Run System." For Portland Water Bureau. January 2002.

Portland Water Bureau. "Discover Your Drinking Water." http://www.portlandonline.com/water/index.cfm?c=49358&a=225481. Accessed October 2010a.

Portland Water Bureau. "Regional Partners." http://www.portlandonline.com/water/index.CFM?c=29883. Accessed October 2010b.

Portland Water Bureau. "Water Management and Conservation Plan for the City of Portland, OR." 2008. http://www.portlandonline.com/water/index.cfm?c=46238&a=179529. Accessed November 2009.

Pullen, J. "Implications of Climate Variability on Western Water Transaction." MS thesis. University of Arizona. 2006.

Pullen, J.L., and B.G. Colby. "Influence of Climate Variability on the Market Price of Water in the Gila-San Francisco Basin," *Journal of Agricultural and Resource Economics*, 33 (2008):473-487.

Real Estate Data Center. "Metropolitan Statistical Area (MSA) Population." http://recenter.tamu.edu/data/popm00/. Accessed April 2010.

Secretary of the Interior. "Record of Decision: Colorado River Interim Guidelines For Lower Basin Shortages and the Coordinated Operations of Lake Powell and Lake Mead." 2007. http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf. Accessed August 2010.

Southern Nevada Water Authority. "Annual Report." 2009a. http://www.snwa.com/html/about_annual_rpt.html. Accessed July 2010.

SNWA. "Water Resource Plan 2009." 2009b. http://www.snwa.com/html/wr_resource_plan.html. Accessed October 2009.

SNWA. "The Colorado River." http://www.snwa.com/html/wr_colrvr.html. Accessed November 2010.

Stratecon Inc. *Water Strategist: Analysis of Water Marketing, Finance, Legislation and Litigation*. Private Publication. 1987-2009.

Truckee Meadows Water Authority (TMWA). "Rule 7: Requirements for Will-Serve Commitment Letters." http://www.tmh2o.com/docs/Customer_Services/rules/Rule07_20080301.pdf. Accessed November 2010.

United States Department of Agriculture (USDA). Economic Research Service. "Farm Income: Data Files." http://www.ers.usda.gov/data/FarmIncome/FinfidmuXls.htm. Accessed March 2010.

United States Geological Survey (USGS). National Water Information System: Web Interface. "USGS Surface-Water Data for Oregon." http://waterdata.usgs.gov/or/nwis/sw. Accessed September 2010.

Woodhouse, C.A., S.T. Gray, and D.M. Meko. "Updated Streamflow Reconstructions for the Upper Colorado River Basin." *Water Resources Research*, 42 (2006).

Wooldridge, J.M. *Introductory Econometrics: A Modern Approach.* South-Western College Publishing. 2000.